THE GRANITIC ROCKS OF SOUTH-WEST ENGLAND

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CONTENTS

I. INTRODUCTION

The origin and mode of emplacement of granitic rocks have for many years been subjects of controversy. Even the granites of south-west England have provided evidence for the two major schools of thought—magmatist and transformist—although the majority of workers do not appear to have questioned a magmatic origin for these rocks. In his introduction to "The Granite Controversy", H. H. Read (1957) considers that although there may be 'granites and granites', these are so related within the *Granite Series* (Read 1955) that they pose no genetic problem. To others, the granite problem remains a reality (see for example, Part XIV of the International Geological Congress Proceedings, Norden, 1960).

Great advances in granite petrology have been made within the last two decades as a result of diligent fieldwork upon well-exposed granites (e.g., Pitcher and Read 1958; Read 1958; Oen 1960), and invaluable experimental work performed on the "granite system" (Tuttle and Bowen 1958; Mackenzie 1960; Orville 1959, 1963). As a result of this work, the authors would agree that there is no granite problem in the broad sense considered by Read (1957) and others.

However, problems still remain, such as the nature of the material at the time of its emplacement, the occurrence in the same body of granite of some features which suggest replacement and others which suggest forceful injection, the nature of the "differentiation" which produces granitic rocks of different character in close association, and the nature and origin of hydrothermal solutions.

This paper has two aims. In the first place, it seeks briefly to review some work on the granites of Devon and Cornwall recently completed and in progress. Secondly, it attempts to assess the contribution to the problems listed above provided by observations on and data from these granites, and to consider some major problems still at issue and suggest how some of these might be tackled.

The granitic rocks considered in this paper occur as six major and several smaller masses, together with dyke phases, emplaced in Upper Palaeozoic sedimentary and basic igneous rocks (Fig. 1). They have the features of typical post-kinematic high-level plutons. Each pluton is roughly circular or ellipsoidal in outline or has arcuate boundaries with the country rocks, and the larger ones are composite in character. Exposed contacts are sharp, and the grade of metamorphism imposed upon the rocks of the aureole never exceeds that of the hornblende-hornfels facies. There is good evidence to show that the plutons lie on a continuous ridge

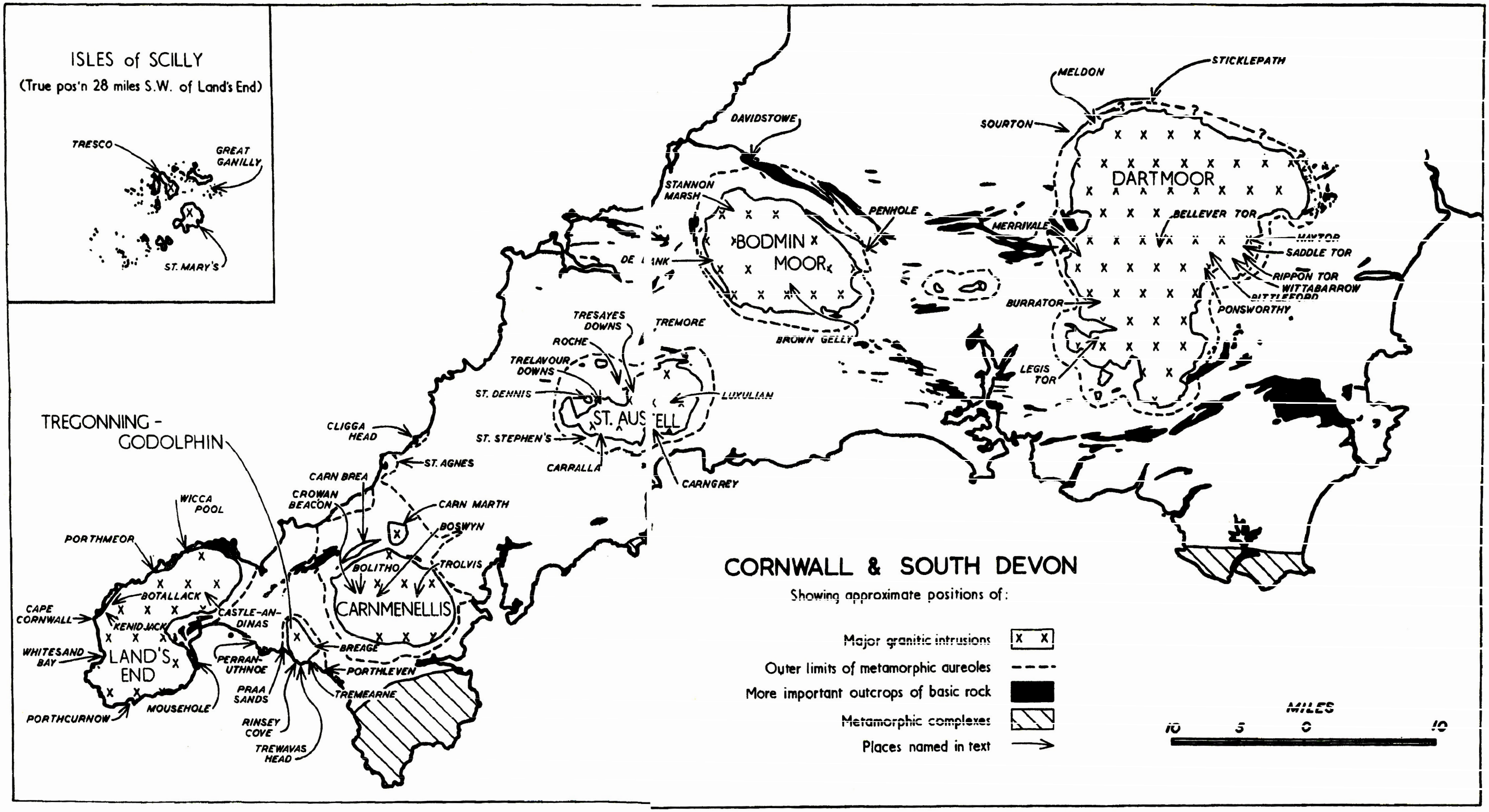

FIG. 1 (map). *Based on Crown Copyright Geological Survey maps by permission of the Controller H.M. Stationery Office.*

of granite which extends from Dartmoor to the Scilly Isles (Davison 1930; Bott *et al.* 1958; Hosking 1962) and that the present outcrops are merely the upward extensions of granite from this ridge. Associated with the ridge is a zone of extensive mineralization (Hosking 1962). The granites were emplaced after the culmination of the Hercynian orogeny at the end of the Carboniferous period or, possibly at the beginning of the Permian (Butcher 1961). Isotopic age determinations indicate a " best " age of emplacement and associated mineralization of 280 $\pm$ 10 m.y. (Long 1962) which is in general agreement with the detailed ages suggested by Miller and Mohr (1964).

II. THE NATURE OF THE GRANITES

A hazard of petrology lies in the difficulty encountered in selecting representative samples for examination and analysis. Generally, this difficulty increases with increasing grain size of a rock, and is particularly serious when apparently homogeneous rocks are in reality heterogeneous with compositional variations too subtle to be detected by inspection. The problem may be largely overcome by a statistical approach, and petrologists are now tending to collect large numbers of specimens in order to assess quantitatively departures from a given (mean) composition and also the significance of the differences both between specimens and between rock types. Such an approach is obviously less likely to suffer from the errors arising from the purely subjective (albeit experienced) sampling techniques hitherto employed.

Although Richardson (1923) made an early attempt at statistical petrology, the methods have only become relatively easy and therefore popular with the improvement of techniques for staining minerals, semi-automatic rapid point-counting devices and computers for handling large amounts of information. The problems involved have been discussed by Austin (1960), Chayes (1955, 1956), Chayes and Suzuki (1963), Exley (1963), Link and Koch (1962), and Whitten (1959, 1961, 1962, 1963).

In Cornwall, Richardson's work (1923) on the St. Austell granite was followed by Exley (1959), who used a similar technique for some of his analyses. Chayes (1955) and Austin (1960) both applied statistical criteria to studies of the Carnmenellis granite, and current work on the granites of Bodmin Moor, Tregonning-Godolphin, Land's End and the Scilly Isles is being carried out statistically.

Apart from these, all the analyses available in the literature are based on the assumption that the specimens analysed were representative, and of this there can be no guarantee. The reader is warned, therefore, that many analyses (however accurate) may be misleading and may, indeed, have led to erroneous conclusions.

Before describing the main types of " granite " found in south-west England, it will be necessary to define two of the terms which we shall use. Firstly, by " porphyritic " we mean a texture in which large feldspar crystals — but not necessarily large quartz grains — occur in a finer-grained matrix. Secondly, by " lithionite " we mean the pale-brown, sometimes faintly lilac mica which is quite common in some of these rocks. We are aware that " lithionite " is an out-of-date name, but in the present situation its use seems to offer advantages. The lithium-bearing micas have not yet been described in any detail, but the work so far carried out indicates that two kinds are to be found. One is zinnwaldite (Exley 1959, pp. 201, 230; Cundy *et al.* 1960) which is trioctahedral, while the other may be either a genuine dioctahedral muscovite containing some lithium or, alternatively, muscovite interlayered with lepidolite (see Levinson 1953). Such micas are not easily distinguished by simple methods, and the term " lithionite " seems to meet our need for a name to cover them both.

There are several main categories of granitic rock, some of which may be subdivided into two or three varieties. Not all necessarily occur in each intrusion, although the main intrusions are usually made up of four or five. The main rock types are now described.

1. **Biotite granites.**

(a) BASIC MICROGRANITES. These are dark fine-grained rocks showing a variable composition and variety of textures from hypidiomorphic to ophitic. Some are porphyritic. *Plagioclase* is about oligoclase-andesine (Brammall and Harwood 1932, Analyses 30-32; Osman 1928; Reid *et al.* 1912), and dominant over potash feldspar in the majority of cases. Micrographic intergrowths are common, at least in Dartmoor examples. *Biotite* is dominant over *muscovite* and is usually present in rather large amounts. The chief accessory minerals are apatite and zircon; tourmaline is rare, and "metamorphic" minerals are absent. Other related dark rocks are of dioritic or even doleritic composition and, according to Brammall (1962A) and Brammall and Harwood (1932), represent less granitized stages in the transformation of pre-existing diabases and similar rocks.

Basic microgranites occur in all the main intrusions as nodules a few inches across, and occasionally as rafts which measure up to several feet in length, as at Bellever Tor (Dartmoor).

(b) COARSE, PORPHYRITIC. This variety constitutes the bulk of the plutonic rocks of south-west England and occurs in all the main masses; it is well seen at Haytor (Dartmoor), the Luxulyan district (St. Austell), Land's End, and the south-eastern part of St. Mary's (Scilly). Several workers have used the wide range of textures and compositions to erect sub-varieties, but until further detailed work is completed the coarse porphyritic biotite granites are best considered as a single type. They are easily distinguished by having a matrix coarser than about 3 mm. average grain diameter and by potash feldspar megacrysts up to 15 cm. long in some cases. The average length of megacrysts is about 3 cm. to 5 cm. The texture is typically hypidiomorphic granular.

Potash feldspar occurs both as megascopically euhedral megacrysts and as anhedral interstitial grains in the groundmass. Twinning on the Carlsbad Law is almost universal and usually the feldspar is coarsely microperthitic and clouded. The albite lamellae consist of branching veinlets and occasionally irregular patches; most are totally enclosed within the host but a few may " penetrate " from a neighbouring plagioclase (Exley 1959; Austin 1960) or even from totally included grains of albite. These have probably resulted from exsolution. Also included may be crystals of any of the other minerals in the rock; for example, plagioclase (usually oligoclase, with narrow albite rims) and biotite (which may be zonally arranged).

In detail, many of the megacrysts have irregular outlines: in the Carnmenellis (Type 2) granite, anhedral megacrysts are not sharply separated from the interstitial potash feldspar (Stone and Austin 1961). This inequigranular-seriate fabric is also found extensively on Bodmin Moor; e.g., in the De Lank granite.

Sufficient data are not yet available to indicate the variation in the state of Al/Si order-disorder of the potash feldspar. Microcline has been reported from Dartmoor (Brammall and Harwood 1932), Bodmin Moor (Ghosh 1927), Carnmenellis (Austin 1960), and Land's End (Reid and Flett 1907), but is probably generally uncommon. Recent X-ray work by Mackenzie and Smith (1962) shows that some potash feldspars from Dartmoor are dominantly orthoclase.

Plagioclase is generally euhedral or subhedral and tabular, with some crystals bent or broken and resealed. Twinning is universal, the commonest laws being albite, Carlsbad and pericline; in addition, Exley (1959) has reported the presence

TABLE 1: *Composition of plagioclase in different types of coase porphyritic biotite granites*

1. Dartmoor	Giant Granite An_{18}		Blue granite $An_{6.5}$
2. Bodmin Moor	Normal An_{30-41}		Godaver $An_{<30}$
3. Carnmenellis	Type 1 An_{30}	Type 2 An_{8}	Type 3 An_{11}

1. Brammall (1926, p. 255), (recalculated An-values)
2. Ghosh (1927, pp. 295, 296)
3. Ghosh (1934, pp. 249, 251, 252)

of Ala B, Carlsbad-albite and albite-Ala B. Three kinds of twinning are often found in one crystal. The contacts between plagioclase and other minerals, especially quartz and potash feldspar, are frequently irregular and indicative of reaction relations; myrmekite has been described from Carnmenellis (Austin 1960) and has been seen in rocks from Bodmin Moor.

Where the coarse porphyritic biotite granite has been separated into a number of types, it is found that the composition of plagioclase varies as shown in Table 1; these figures indicate a tendency for the anorthite content of the plagioclase to diminish in what are regarded as the later types of rock.

Normal zoning is usual in plagioclase and there is often a difference in composition of about 20 per cent An between core and rim. Austin (1960) has recorded oscillatory zoning in the Carnmenellis granite. The mineral shows varying degrees of cloudiness and often alteration to mica or clay; as is usual, the inner parts of a zoned crystal decompose first.

Quartz is anhedral with frequent large crystals adding to the porphyritic appearance of the rock. Individual crystals of this kind, which may measure 1.5 cm. across, are to be distinguished from similar-sized aggregates of anhedral quartz grains. All the large quartz grains are strained, and Austin (1960) notes that some of the quartz aggregates are unusually severely strained and have sutured margins. Quartz also occurs as interstitial grains and inclusions in the two feldspars; these grains are often unstrained.

TABLE 2: *Chemical analyses of some biotites*

	1	2	3	4	5
Weight per cent.					
SiO_2	35.06	36.23	39.92	33.93	34.59
TiO_2	2.16	2.50	—	1.39	1.77
Al_2O_3	18.40	21.78	22.88	20.55	20.26
Fe_2O_3	4.11	1.95	2.32	3.91	3.48
FeO	18.83	18.23	15.02	18.79	18.45
MnO	0.65	0.65	1.40	0.43	0.48
MgO	5.72	4.20	1.07	5.61	5.24
CaO	0.40	0.82	0.68	0.35	0.66
Na_2O	0.36	2.07	0.99	0.40	0.53
K_2O	8.68	7.87	9.76	9.05	8.30
H_2O+	2.75	3.30	—	3.40	4.51
H_2O-	0.54	—	—	1.41	1.00
F	1.96	0.79	2.12	0.90	0.67
Parts per million					
B	—	—	—	179*	—
Be	10	—	—	—	—
Ga	140	—	—	—	—
Cr	80	—	—	tr	tr
V	85	—	—	273*	273*
Sn	15	—	—	—	—
Li	1800	1120*	7980*	875*	1490*
Ni	20	—	—	—	—
Co	10	—	—	—	—
Zr	150	—	—	—	—
Sr	220	—	—	—	—
Pb	15	—	—	—	—
Ba	120	—	—	179*	tr
Rb	3500	—	—	—	—
Cs	1350	—	—	—	—

(Contd. on next page)

(From previous page)

TABLE 2 *Cations on a basis of 24 (O, OH, F)*

	1	2	3	4	5
Si	5.43	5.45	6.27	5.26	5.24
Al	2.57	2.55	1.73	2.74	2.76
Al	0.80	1.31	2.50	1.01	0.86
Ti	0.25	0.28	—	0.17	0.20
Fe^{3+}	0.48	0.22	0.27	0.45	0.20
Li	0.22	0.15	1.08	0.13	0.20
Mg	1.33	0.94	0.25	1.30	1.18
Fe^{2+}	2.44	2.29	1.97	2.43	2.34
Mn^{2+}	0.08	0.08	0.19	0.06	0.06
Na	0.11	0.60	0.30	0.11	0.16
Ca	0.07	0.13	0.11	0.06	0.11
K	1.71	1.51	1.95	1.80	1.60
Rb	0.04	—	—	—	—
OH	2.85	3.31	—	3.51	4.56
F	0.96	0.37	1.05	0.45	0.32
(OH + F)	3.81	3.68	(1.05)	3.96	4.88
Y group	5.60	5.27	6.26	5.55	5.24
X group	1.93	2.24	2.36	1.97	1.87

1. From adamellite, Bosahan, Carnmenellis (Analysis 1(B), Tables 1 and 2, Butler 1953).
2. De Lank Quarry, Bodmin Moor (Analysis 1, p. 54, Reid *et al.* 1910).
3. Carn Bosavern, Land's End (Analysis II, p. 54, Reid *et al.* 1910).
4. Giant granite, Saddle Tor, Dartmoor (Analysis 67, Brammall and Harwood 1932).
5. Blue granite, Haytor (E) Quarry, Dartmoor (Analysis 64, Brammall and Harwood 1932).

Formulae calculated on basis O + OH + F = 24 and tetrahedral Si + Al = 8, by Butler (1953) (columns 1 and 4) and the authors (columns 2, 3 and 5).

*Converted from percentages in the Tables cited.

Muscovite is present in varying amounts but has a similar appearance in all varieties of this granite. It occurs as clear flakes (up to 3 mm.) usually rather ragged, and is often intergrown with biotite.

Like muscovite, the amount of *biotite* is variable and the mineral occurs in several different associations. It may be intergrown with muscovite, form separate crystals, occur as inclusions (often zonally arranged) in potash feldspar megacrysts, or be concentrated into aggregates associated with andalusite or recognizable xenoliths, or occur as drawn-out biotitic streaks (Austin 1960; Stone and Austin 1961). It has the usual properties of biotite with $2V_X$ ranging from 0 degrees to 15 degrees. Among the included minerals are zircon (usually plentiful and surrounded by pleochroic haloes), apatite, ores and, occasionally, rutile (especially when the host is chloritized).

Reid and Flett (1907) would regard this biotite as lithionite, and all the Survey officers remark on its lithium content. Brammall and Harwood (1932, p. 184) point out that the micas are transitional between biotite and lepidomelane. Chemical analyses are given in Table 2; these have been recalculated as cations on a basis of 24 (O, OH, F) atoms. It can be seen that the biotite from the later Dartmoor term

TABLE 3: *Modal analyses of some coarse porphyritic biotite granites*

	1	2	3	4	5	6	7	8	9	10
Quartz	33.7	40.0	30.0	37.4	35.0	33.3	32.2	30.1	42.1	28.7
Potash feldspar	31.7	25.3	34.6*	26.5*	34.0*	31.3*	30.5	30.4	33.2*	32.3
Plagioclase	21.2	19.6	23.3*	26.0*	24.2*	25.3*	25.1	25.8	15.7*	26.0
Biotite	9.8	7.0	5.0	2.8	4.6	6.2	5.3	5.7	5.2	5.1
Muscovite	0.7	3.2	5.6	5.7	1.4	2.2	5.6	6.4	2.6	5.6
Tourmaline	0.9	2.7	0.8	1.1	0.6	1.3	0.5	0.4	0.3	0.3
Andalusite	—	—	0.2	tr	—	—	0.3	0.5	0.7	tr
Topaz	—	—	—	—	—	0.2			—	0.1
Apatite	0.6	0.3	0.3	0.3	0.1	—	0.5	0.5	—	0.7
Zircon	1.3	1.8	tr	0.1	—	0.2			tr	0.5
Others			0.1	tr	—				—	0.4
	99.9	99.9	99.9	99.9	99.9	100.0	100.0	99.8	99.8	99.7

1. Giant granite, Saddle Tor, Dartmoor (Analysis 12, Brammall and Harwood 1932).
2. Blue granite, Haytor (E) Quarry, Dartmoor (Analysis 2, Brammall and Harwood 1932).
3. Ghosh (1927) 'Normal' granite, Tregarrick Tor, Bodmin Moor (C. S. Exley, unpublished).
4. Ghosh (1927) 'Godaver' granite, Lowlands Down, Bodmin Moor (C. S. Exley, unpublished).
5. Biotite-muscovite granite, Goldenpoint Quarry, St. Austell (S. C. Exley, unpublished).
6. Biotite-muscovite granite, Helman Tor, St. Austell (Table 1, Exley 1959).
7. Ghosh (1934) Type 1 granite, Carnmenellis (Table 1, Chayes 1955).
8. Ghosh (1934) Type 2 granite, Carnmenellis (Table 1, Chayes 1955).
9. Biotite granite (mean of 3), Land's End (B. Booth, unpublished).
10. Biotite granite (G1), Scilly Isles (D. L. Jones, 1963).

NOTE. Analyses 1 and 2 are calculated from chemical analyses; the others are proportions by volume.

*Secondary mica and clay calculated into feldspars.

TABLE 4: *Chemical analyses of some coarse porphyritic biotite granites*

	1	1a	2	3	4	5	6
SiO_2	71.2	0.55	73.66	71.50	71.95	72.15	72.39
TiO_2	0.4	0.11	0.16	0.27	0.44	0.18	0.16
Al_2O_3	14.0	0.23	13.81	14.50	14.63	14.84	14.33
Fe_2O_3	0.5	0.18	0.21	2.90*	0.46	0.41	0.43
FeO	2.3	0.55	1.51	—	1.64	1.47	1.35
MnO	0.1	0.02	0.06	—	0.02	0.03	tr
MgO	0.6	0.21	0.45	0.36	0.69	0.21	0.03
CaO	1.6	0.12	0.67	0.74	1.47	1.17	1.05
Na_2O	3.0	0.16	2.89	2.76	2.02	3.17	3.69
K_2O	4.9	0.23	5.02	6.02	5.46	5.14	4.66
Li_2O	—	—	tr	—	—	—	—
P_2O_5	0.2	0.02	0.24	—	0.34	0.43	0.20
B_2O_3	—	—	—	—	0.14	0.20	0.23
H_2O+	0.9	0.22	1.25	—	0.56	0.74	0.84
H_2O-	0.3	0.14	0.41	—	0.17	0.10	0.15
F	—	—	—	0.16	—	—	—
	100.0		100.34	99.21	99.99	100.24	99.51

1. Average Dartmoor "Giant" granite (mean of 7 analyses from Brammall and Harwood 1932).
1a. One standard deviation of values given in column 1.
2. Dartmoor "Quarry" or "Blue" granite. Lower horizon of Haytor Quarry (Analysis 7, Brammall and Harwood 1932).
3. Biotite-muscovite granite, St. Austell (Exley 1959. SiO_2 and Al_2O_3 from Exley 1956, Table 2).
4. Type 1 granite, Polkanuggo Quarry, Carnmenellis (Ghosh 1934).
5. Type 2 granite, Ponsanooth Quarry, Carnmenellis (Ghosh 1934).
6. Type 3 granite, top of Carnmenellis (Ghosh 1934).

* Total Fe as Fe_2O_3.

(" Blue " granite) is richer in iron and lithium and poorer in magnesium than the biotite from the earlier term (" Giant " granite).

Many *accessory minerals* are found, of which *tourmaline* is probably the most widespread. Other accessories are *topaz* and *andalusite* (both altered to secondary mica), *cordierite* (often altered to pinite), *sillimanite, apatite* (in both small euhedral crystals and larger anhedral cloudy grains), *zircon, rutile, anatase, brookite, fluorite, garnet* and various *ore minerals.*

Modal and chemical data for a number of coarse porphyritic biotite granites are given in Tables 3 and 4 respectively.

(c) FINE, PORPHYRITIC. Generally this variety has a matrix of average grain-size about 2 mm. to 3 mm. Feldspar megacrysts are fewer than in the coarse granite and attain only about 2 cm. in length at most. The texture of these rocks ranges from fairly normal hypidiomorphic to aplitic and although mostly porphyritic, may be non-porphyritic occasionally. The suite of important minerals is similar to that found in the coarse-grained granites. *Potash feldspar* occurs both as megacrysts and in the groundmass; in the former it is microperthitic, less well-shaped than in the coarse granite and is often intergrown with quartz to give a granophyric texture. *Plagioclase* is subhedral and is more albitic than in the coarse rock; Ghosh (1927) suggests An_{15} — An_{10} for the Bodmin Moor variety. *Quartz* is anhedral and

TABLE 5: *Modal analyses of some fine porphyritic biotite granites lithionite granites and a fluorite granite*

	1	2	3	4	5	6	7	8	9
Quartz	32.6	37.8	33.4	36.8	35.0	36.1	30.3	28.2	28.5
Potash feldspar	22.6	27.1	34.2*	28.7	39.3	22.1	18.8	23.9	17.8
Plagioclase	34.3†	22.8†	24.0	16.9	11.6	24.2	28.8	35.8	35.0
Biotite	3.3	2.6	5.6	3.4	4.4	—	—	—	—
Lithionite	—	—	—	—	—	3.7	8.9	6.5	—
Muscovite	3.9	6.1	2.4	4.9	6.5	—	—	—	5.3
Secondary mica	2.7	0.7	—	7.8	—	9.2	9.2	—	10.8
Tourmaline	0.5	2.7	tr	0.9	0.7	3.8	0.1	2.4	0.1
Andalusite	—	—	0.1	0.3	0.3	—	—	—	—
Topaz	—	—	—	—	0.1	0.4	2.1	2.5	0.4
Apatite	0.1	0.1		tr	0.8	0.1	0.8	0.2	0.4
Zircon	—	—	0.3	0.1	0.8	—	—	—	—
Fluorite	—	—		—	—	0.3	1.1	—	1.6
Others	—	—		tr	0.9	—	—	0.5	—
	100.0	99.9	100.0	99.8	100.4	99.9	100.1	100.0	99.9

1. Biotite granite, Harrowbridge Hill, Bodmin Moor (C. S. Exley, unpublished).
2. Biotite granite, Dozmary Pool, Bodmin Moor (C. S. Exley, unpublished).
3. Biotite granite, summit of Godolphin Hill (M. Stone, unpublished).
4. Biotite granite, Castle-an-Dinas, Land's End (B. Booth, unpublished).
5. Biotite granite (G2), Scilly Isles (D. L. Jones 1963).
6. Coarse porphyritic lithionite granite (mean of 4 modes), St. Austell (Table 1, Exley 1959).
7. Non-porphyritic lithionite granite (mean of 3 modes), St. Austell (Table 1, Exley 1959).
8. Non-porphyritic lithionite granite, Trewithick (Tregonning granite) (M. Stone, unpublished).
9. Fluorite granite (mean of 6 modes), St. Austell (Table 1, Exley 1959).

*Includes 6.1% of muscovite in potash feldspar. †Includes clay.

TABLE 6: *Chemical analyses of some fine porphyritic biotite granites lithionite granites and a fluorite granite*

	1	2	3	4	5	6
SiO_2	72.1	73.00	73.4	72.5	71.1	72.2
TiO_2	0.28	0.15	0.10	0.09	0.06	0.3
Al_2O_3	14.29	14.44	14.8	15.9	15.99	15.1
Fe_2O_3	1.11	0.32	1.32*	1.1*	0.99	0.25
FeO	1.16	0.90	—	—	0.18	—
MnO	0.04	0.01	0.01	0.01	0.06	0.004
MgO	0.51	0.32	0.32	0.07	0.28	0.08
CaO	0.50	0.33	0.87	0.35	0.49	1.7
Na_2O	2.45	0.32	2.52	3.43	4.32	3.92
K_2O	5.98	8.01	4.63	4.70	4.48	4.58
Li_2O	0.05	—	0.007	0.026	0.31	0.006
P_2O_5	0.25	tr	—	—	0.48	—
B_2O_3	0.17†	0.91	—	—	—	—
H_2O+	0.53	0.85	—	—	0.33	—
H_2O-	—	0.15	—	—	—	—
F	0.12	—	0.38	1.5	1.22	1.36
	99.54	99.71			100.29	
Less $O-=F$	0.05				0.51	
	99.49				99.78	

1. Fine porphyritic biotite granite, summit of Godolphin Hill (*New analysis.* Analyst: M. Stone).
2. Fine granite, eastern portion of Bolitho-Boswyn mass, Carnmenellis (Analysis 8, Ghosh 1934).
3. Porphyritic lithionite granite (mean of 3 analyses), St. Austell (Table 1, Exley 1959. SiO_2 and Al_2O_3 from Exley 1956, Table 2).
4. Non-porphyritic lithionite granite, St. Austell (Table 1, Exley 1959. SiO_2 and Al_2O_3 from Exley 1956, Table 2).
5. Non-porphyritic lithionite granite, Trewithick (Tregonning granite). (*New analysis.* Analyst: M. Stone).
6. Fluorite granite (mean of 3 analyses), St. Austell (Table 1, Exley 1959. SiO_2 and Al_2O_3 from Exley 1956, Table 2).

*Total Fe as Fe_2O_3. †B_2O_3 analysed by M. G. Bawden.

interstitial and does not occur in large "porphyritic" crystals or aggregates except in the Carnmenellis mass. The *micas* are similar to those in the coarse granite but *biotite* is commonly subordinate to *muscovite* and in some case it is absent. The chief *accessory minerals* are *tourmaline, topaz* (which seems to be unusually abundant: e.g. Ghosh 1927; Reid and Flett 1907) and *cordierite* (altered to pinite). *Andalusite* is rare.

Granite of this kind occurs in most of the main intrusions; e.g., at Bellever Bridge (Dartmoor), near Brown Gelly (Bodmin Moor), Crowan Beacon (Carnmenellis), Castle-an-Dinas (Land's End), and southern Tresco (Scilly Isles), but is apparently rare in the St. Austell intrusion. The granite of Godolphin Hill is a fine porphyritic biotite granite, but has many of the chemical and mineralogical features of the coarse varieties. Mineral (modal) and chemical analyses are given in Tables 5 and 6 respectively.

2. **Lithionite granites.**

(a) COARSE, PORPHYRITIC. At present, the only certain occurrence of this variety is in the central and extreme western parts of the St. Austell mass, although it is likely that the granites of Cligga Head and St. Agnes are of this type.

The texture of these rocks is very similar to that of the coarse porphyritic biotite granites, but the grain size is smaller in both megacrysts and groundmass. The latter has an average grain size of about 4 mm. while the megacrysts, which range from 1.5 cm. to 4 cm. in length, average about 2.5 cm. The part of the St. Austell granite occupied by this kind of rock is extensively altered and contains most of the china clay pits in the district. Completely fresh specimens are hard to find.

Potash feldspar is again the most obvious mineral and as elsewhere is subhedral to anhedral, the shape being better in the megacrysts than in the groundmass. The majority of other minerals are represented as inclusions, of which plagioclase is the most abundant. Though commonly coarsely microperthitic, the feldspar is sometimes cryptoperthitic. It is often altered to quartz and secondary mica. *Plagioclase* shows the features already described together with occasional " chessboard " twinning. The mineral is not zoned and has a composition of An_7 (Exley 1959). Apart from the white " secondary " mica, the only mica is *lithionite* or *zinnwaldite* which occurs as brown flakes with variable pleochroism. Some crystals contain pleochroic haloes round zircon crystals. Richardson (1923) records $2V_X$ as $18\frac{1}{2}$ degrees to 31 degrees; Exley (1959) reports $2V_X$ as ranging from 10 degrees to 17 degrees and from 28 degrees to 36 degrees with $N_Y = 1.578 - 1.590$. *Quartz* is anhedral, interstitial and cloudy and is nearly always strained. Occasional large aggregates occur. The *accessory minerals* include anhedral brown or blue *tourmaline* (sometimes zoned), *apatite* (euhedral grains in feldspar; anhedral cloudy grains associated with mica), anhedral *topaz*, and rare *fluorite* in small interstitial purple grains. A modal analysis of this type of granite is given in Table 5, column 4, and a partial chemical analysis is given in Table 6, column 3.

(b) NON-PORPHYRITIC. The two main occurrences of this rock type are in the west-central part of the St. Austell outcrop and the major part of the Tregonning-Godolphin granite. The outstanding features of these rocks is their even medium grain and typically granitic texture. Mineralogically, they are much like the porphyritic variety but there are some differences. *Plagioclase* is not zoned and has a composition of An_4 to An_2 (Exley 1959; Stone, unpublished). *Quartz* does not form large aggregates and has a sub-reticulate pattern of inclusions. In the Tregonning granite, millimetre-grained quartz crystals have been recrystallized to aggregates of unstrained crystals (0.2 mm. to 0.5 mm. across). Lithionite has $2V_X$ of 22 degrees to 34 degrees and N_X = 1.567 to 1.575 (Exley 1959). The same suite of *accessory minerals* is found. Modal and chemical data are given in Tables 5 and 6 respectively.

In the St. Austell granite, this type of rock occurs in patches within the fluorite granite of the St. Dennis—St. Stephens district. There appears to be no structural or textural break between the two rock types.

3. **Fluorite granite.**

Although fluorite is not rare as an accessory mineral in the granitic rocks of south-west England, there is only one locality where it occurs persistently in sufficient quantity to justify regarding its host rock as a distinct variety. This is in the St. Stephens—St. Dennis district of the St. Austell granite. The rock is uniform, medium-grained and remarkably deficient in dark minerals. *Potash feldspar* is usually anhedral or subhedral, encloses albite crystals and is micro- or cryptoperthitic. Most is rather cloudy and slightly altered to quartz and secondary mica, but some is clear and interstitial. *Plagioclase* is euhedral or subhedral, unzoned and has a composition of An_4 (Exley 1959). " Chessboard " twinning occurs occasionally in larger crystals. *White mica,* referred to as "gilbertite" by Richardson (1923) is the main mica and has $2V_X$ from 26 degrees to 34 degrees with N_Y = 1.587—1.593 (mean 1.591); these properties are close to Winchell's (1951) picrophengite or the normal muscovite of Deer, Howie and Zussman (1962). The chief *accessory minerals* are *fluorite* (purple, either in mica cleavages or interstitial), *topaz* (anhedral), *apatite* (always cloudy and strained) and rare *tourmaline.*

A modal analysis is given in Table 5 (column 7) and a partial chemical analysis in Table 6 (column 6).

4. **Minor rock types.**

(a) LEUCOGRANITES. All the main granite masses contain facies that are markedly deficient in mafic minerals; these range from coarse hypidiomorphic varieties such as those found in irregular patches in the Carnmenellis granite, through medium-grained types, such as occur in association with aplites and pegmatites at Tremearne and Porthmeor, to microgranites occurring as intrusive veins and apophyses and the " chilled " margin of the Stage 3 (" Quarry ") granite which is seen at Haytor rocks and elsewhere in eastern Dartmoor.

The range of composition and texture covered by rocks of this kind is so wide that a comprehensive account is difficult. Broadly, however, they may be considered as belonging to three main categories..

(i) Coarse-grained quartzo-feldspathic " segregations ", associated in most cases with coarse-grained biotite granite. Brammall and Harwood (1923) describe such a rock from Wittabarrow, Dartmoor, as " . . . . a cream-coloured coarsely crystalline rock without phenocrysts, and composed essentially of feldspar and quartz ". Its chemical composition is given in Table 8 (column 4). A description of a leucogranite from Carnmenellis (Ghosh 1934) says, " The leucocratic variety . . . . is composed essentially of plagioclase, with a little quartz, scanty orthoclase and rutile. The plagioclase $Ab_{91}An_9$ is clouded by decomposition. This variety grades into others richer in quartz and orthoclase . . . . ". Austin (1960), also referring to the Carnmenellis granite, states that such segregations are more common in the 'Type 1' granite than in the others; that they may reach two feet or more in length, and that they consist of potash feldspar and quartz.

(ii) Medium- to fine-grained leucogranites that occur as veins or dykes. These are well-developed in the banded roof-zone of the Tregonning granite, and in the Tremearne sheets (It is proposed to refer to both these sets of rocks as the 'Banded Complex'). The leucogranites of the Banded Complex have close chemical and mineralogical affinities with the nearby non-porphyritic lithionite granite (Tregonning granite). They are millimetre-grained rocks whose texture ranges from hypidiomorphic equigranular to inequigranular-seriate. In some specimens, " pools " of millimetre-grained material (albite subordinate to potash feldspar) are set in a network or amongst patches of aplitic material (grain size less than 0.5 mm., rich in albite, potash feldspar generally scarce).

TABLE 7: *Modal analyses of leucogranites and aplites*

	1	2	3	4	5
Quartz	24.2	25.1	37.6	25.8	31.3
Potash feldspar	19.0	18.9	42.5	10.9	19.4
Plagioclase	42.5	40.3	10.8	46.5	34.2
Biotite	—	—	2.0	—	—
Lithionite	9.4	8.0	—	13.0	11.7
Muscovite	—	—	3.7	—	—
Tourmaline	0.2	1.5	2.0	0.8	—
Topaz	2.5	5.7	—	3.0	2.9
Amblygonite	1.7	—	—	—	0.3
Apatite	—	0.1	0.4	—	0.3
Zircon	—	—	1.0 (Zircon + Others)	—	—
Others	0.5	0.3		—	—
	100.0	99.9	100.0	100.0	100.1

1. Amblygonite-bearing leucogranite, near roof of Tregonning granite, Rinsey (M. Stone, unpublished).
2. Leucogranite, Megiliggar Rocks, Tremearne (M. Stone, unpublished).
3. Fine leucogranite, Haytor Rocks (Analysis 3, Brammall and Harwood 1932).
4. Aplite from near roof of Tregonning granite, Trewavas Head (M. Stone, unpublished).
5. Aplite, Megiliggar Rocks, Tremearne (M. Stone, unpublished).

TABLE 8: *Chemical analyses of some leucogranites and aplites*

	1	2	3	4	5
SiO_2	71.3	74.68	72.4	73.16	74.41
TiO_2	0.03	0.16	0.03	0.04	0.08
Al_2O_3	16.31	13.25	15.00	13.95	14.21
Fe_2O_3	0.19	0.72	0.25	0.03	0.23
FeO	0.26	0.71	0.58	0.47	0.21
MnO	0.10	0.02	0.07	0.01	0.007
MgO	0.28	0.25	0.30	tr	0.03
CaO	0.17	0.48	0.25	0.43	1.00
Na_2O	5.08	2.66	4.15	2.57	5.79
K_2O	4.15	5.42	4.83	8.16	3.43
Li_2O	0.53	tr	0.39	tr	tr
P_2O_5	0.74	0.19	0.39	0.16	0.37
B_2O_3*	0.10	—	n.d.	—	—
H_2O+	0.07	0.93	0.17	0.31	0.19
H_2O-	—	0.60	—	0.33	0.10
F	1.41	—	0.99	—	0.01
	100.72	100.07	99.80	99.62	100.07
Less O − = F	0.59		0.42		
	100.13		99.38		

1. Amblygonite-bearing leucogranite, near roof of Tregonning granite, Rinsey (*New analysis.* Analyst: M. Stone).
2. Fine-grained leucogranite, intrusive below Tor (Giant) granite, Haytor Rocks, Dartmoor (Analysis 3, Brammall and Harwood 1932).
3. Aplite, Megiliggar Rocks, Tremearne (*New analysis.* Analyst: M. Stone).
4. Leucogranite, in intrusive relation to Tor (Giant) granite, Wittabarrow, Dartmoor (Analysis 8, Brammall and Harwood 1932).
5. Felsite, Ludbrook, near Bittaford Bridge, Dartmoor (Analysis 4, Brammall and Harwood 1932).

*B_2O_3 analysis by M. G. Bawden.

Potash feldspar is generally interstitial, perthitic and has $2V_X$ between 48 degrees and 81 degrees. *Plagioclase* is nearly pure albite (An_3); it is subhedral to euhedral and sometimes strained. *Quartz* occurs as equant anhedral millimetre-sized grains as well as smaller, often rounded inclusions in both feldspars. *Lithionite* forms ragged anhedral flakes, often slightly pleochroic. Calculations based on the modes and chemical analyses (Table 7, column 1; and Table 8, column 1) indicate that in the unaltered leucogranites of the Banded Complex the mica is rich in the zinnwaldite component (Stone, unpublished). *Accessory minerals* include *tourmaline* (pale golden yellow, slightly pleochroic, poikiloblastic millimetre-sized grains), *topaz, amblygonite,* anhedral *apatite* and *ore minerals.*

(iii) In some cases, leucogranite may be a facies of some other variety. This is probably true of the example at Haytor Rocks (Dartmoor), whose composition is given in Table 7 (column 3) and Table 8 (column 2). Plagioclase in the leucogranites is always albite; at Haytor Rocks it has the composition An_2 (Brammall and Harwood 1932).

(b) APLITES. These are fine-grained, leucocratic saccharoidal rocks which occur in all the main masses usually as small dykes and veins but occasionally as part of the matrix of other varieties (e.g., leucogranites, pegmatites and porphyritic granites). They are essentially equigranular, although inequigranular and porphyritic varieties (with feldspar megacrysts measuring up to 1.5 cm. in length) are known. *Potash feldspar* is generally interstitial and perthitic, but it sometimes forms larger grains which include other minerals, particularly albite and quartz. *Plagioclase* forms subhedral to anhedral tablets having a composition close to pure albite (An_4 in the Carnmenellis mass according to Ghosh (1934) and An_{2-3} in the Banded Complex of the Tregonning-Godolphin granite). *Quartz* is anhedral and interstitial, often having amoeboid outlines and sometimes encloses or partly encloses subhedral laths of albite in poikilitic fashion. The *micas* include *muscovite* and brown mica which may be *biotite* or a *lithium-bearing* species depending upon the "environment" of the aplite. Thus, aplites cutting biotite granites contain biotite, whilst those associated with lithionite granites contain lithionite. *Accessory minerals* include *tourmaline, topaz* and *ores.* Austin (1960) has separated the aplites of the Carnmenellis mass into four groups according to their textures and field relations.

The aplites of Tremearne and Porthmeor present some complex and interesting features. In both cases, they are closely associated with both pegmatites and leucogranites and they are often banded. The banding, which is roughly parallel to contacts or to the outlines of xenoliths, is due to both mineralogical and textural variation. Sometimes, this variation gives rise to a fine rhythmic banding or "line" rock (see Schaller 1925; Jahns 1955); in other cases the banding results from centimetre- to decimetre- scale alternations of aplite and pegmatite. "Graded" units in which the grain size and tourmaline content increase downwards occur in aplite associated with lithionite granite at Tremearne. These resemble occurrences described from south-west Greenland by Harry and Emeleus (1960). The lower part of a "graded" unit is often irregular and shows features reminiscent of "bottom structures" in sedimentary rocks or of replacement features such as those described from aplite/pegmatites in the U.S.S.R. by Uspensky (1943).

Modal and chemical data for aplites from the Tregonning-Godolphin granite complex are given in Tables 7 (columns 4 and 5) and 8 (column 3). A felsite analysis from Dartmoor is given in Table 8 (column 5) for comparison.

(c) PEGMATITES. In view of the high proportion of volatile constituents in these granites, pegmatites are remarkably scarce. Only three or four are known to have been sufficiently well-developed to be worked for their mineral content; e.g., the 50 yards wide Tresayes Down pegmatite near Roche, which consisted essentially of alkali feldspars with small amounts of quartz and tourmaline and the lithionite pegmatite on Trelavour Downs (Ussher *et al.* 1909).

The most usual suite of minerals found in the pegmatites of the South West consists of *potash feldspar* (often perthitic), *albite, quartz, muscovite* (or the greenish variety commonly described as *gilbertite*), a dark brown mica which may be either *biotite* or the paler *lithionite* and *tourmaline*.

Pegmatites having more or less this composition, with Carlsbad or Baveno-twinned potash feldspar as the dominant mineral, occur in all the main granites either as irregular pod-like masses or as veins.

The pegmatites of the Tremearne cliffs are of particular interest because of the way in which the wedge-shaped potash feldspar crystals (up to 15 cm. in length) and long tourmaline prisms have grown perpendicularly to the upper surfaces of the pegmatite sheets and because of the intimate relations between pegmatite and aplite (Hosking 1952; Stone and Austin 1961).

Pegmatites having unusual compositions have been described from Dartmoor; thus from the Ponsworthy district Reid *et al.* (1912) have described a rock consisting of " red orthoclase and green chloritised feldspar (gilbertite) with quartz and schorl or rarely a small amount of biotite ". The same authors have also described from Bittleford Down a pegmatite made up of potash feldspar, oligoclase, quartz, anhedral hornblende and euhedral sphene.

Complex pegmatites appear to be unusual, but Hosking (1954) has described examples from Trolvis in the east central part of the Carnmenellis granite. In these, in addition to the minerals already mentioned, fluorite, bertrandite and chalcedony were found. Hosking notes that the shapes of the crystals and the way in which one generation grew upon another suggest a preferred direction of growth and hence of movement of pegmatitic liquid.

5. Elvans.

The term " elvan " is now commonly restricted to dyke- (or sill-) forming granite-porphyries, although formerly it also included other minor intrusives, particularly diabases.

Granite porphyries occur in moderate numbers throughout the peninsula and are intruded into both granite and country rocks. They occur typically as steeply-dipping dykes having a maximum thickness of *ca.* 150 feet (as in parts of the White-sand Bay—Porthcurnow example) but usually measuring between 20 feet and 40 feet across. Many are much narrower than this. A few elvans have a " sill-like " form; e.g. the Penhole elvan on the east side of Bodmin Moor (Reid *et al.* 1911) and the Breage elvan (Hall 1930). Elvans also occur as inclusions in porphyritic granite on Dartmoor (Brammall 1926 p. 257) and an elvan veined by non-porphyritic lithionite granite occurs west of Legereath Zawn (Tregonning-Godolphin).

In appearance the elvans are light or dark grey or pink or greenish rocks with chilled contact facies becoming coarser towards the interior. The chilled margins have variously been described as " felsitic " (Reid *et al.* 1910) " sub-vitreous "

(Ussher 1912) or "rhyolitic" (Austin 1960). Such terms give an indication of the grain-size and also suggest the presence of ' fluxion " banding, which frequently occurs, not only in the selvedge but also in the inner parts of the dykes. The majority of elvans are porphyritic, and generally, just as the grain-size of the groundmass varies, so the megacrysts also become larger away from the margins. Reid and Flett (1907) observe that there is often an inverse relation in the Land's End elvans between the fluxion banding and the number of megacrysts. Some elvans are non-porphyritic to feebly porphyritic. The Trevean elvan, near Perranuthnoe, is an example: it contains occasional small (0.5 cm.) megacrysts of potash feldspar, is banded throughout and contains xenoliths or "segregations" of medium-grained granitic material. Multiple intrusions have been noted at Tremore, to the north of St. Austell (Ussher *et al.* 1909), and at Praa Sands (Stone, unpublished). In all cases, there is remarkably little metamorphism of the adjacent country rocks.

Elvans have as their megacrysts *quartz, feldspar* and sometimes *mica.* The first of these is usually in the form of bipyramidal crystals, frequently somewhat rounded or "corroded" and containing liquid inclusions. The feldspar is commonly white or pink microperthite in subhedral crystals, sometimes enclosing other minerals and having Carlsbad twinning. Microcline occurs in elvans in the Carnmenellis mass (Austin 1960). Where *plagioclase* is found, it is oligoclase or albite and often altered to secondary mica. Ghosh (1934) records that plagioclase megacrysts from an elvan in the Carnmenellis granite have a composition of $Ab_{83}An_{17}$, whilst plagioclase enclosed in perthite is $Ab_{89}An_{11}$. Both *biotite* and *muscovite* also occur as megacrysts on occasions: they are generally in the form of six-sided prisms. The former (which may in some cases be a lithia mica) is particularly common in the Penhole elvan mentioned above, whilst the latter is present in some elvans of the St. Austell district (Ussher *et al.* 1909).

Amongst other easily recognised minerals, though not occurring as megacrysts, are variable amounts of *tourmaline,* both euhedral brown "primary", as at Land's End (Reid and Flett 1907) and blue "secondary", *apatite, topaz* (absent from Land's End), *pinite* (after cordierite, especially in the Land's End district and in the Praa Sands elvan) and *zircon,* usually included in mica and surrounded by pleochroic haloes. *Fluorite* has replaced feldspar near St. Austell (Ussher *et al.* 1909).

The groundmass is mainly microgranitic in texture, consisting of quartz and potash feldspar, often with secondary white mica. A micrographic texture is common, particularly round megacrysts.

The relations between the Dartmoor felsites, first described by Worth (1902 and 1903) and the elvans are difficult to interpret. It seems possible that the former represent a pre-granite series of intrusions or an early stage in granite emplacement, representing virtually uncontaminated material (Brammall and Harwood 1932).

Chemical analyses of some elvans, including two new analyses, are given in Table 9. The main feature shown by the new analyses is the decrease in K_2O close to the margin of the Tregonning elvan (column 6) when compared with the centre (column 5). Preliminary data on the Praa Sands elvan indicate a difference of the same order.

TABLE 9: *Chemical analyses of Elvans*

	1	2	3	4	5	6
SiO_2	72.51	71.46	70.77	72.43	71.8	73.8
TiO_2	n.d.	n.d.	0.32	n.d.	0.19	0.22
Al_2O_3	13.31	15.38	16.08	18.08	13.77	13.28
Fe_2O_3	tr	0.30	0.47	2.20	1.61	2.17
FeO	3.87	2.27	1.63	—	1.33	0.87
MnO	0.62	tr	0.06	tr	0.06	0.04
MgO	1.52	0.22	0.50	tr	0.45	0.45
CaO	0.60	0.47	2.06	tr	0.44	0.31
Na_2O	0.43	2.79	1.41	4.12	0.09	0.14
K_2O	6.65	5.51	5.80		8.50	6.89
Li_2O	n.d.	n.d.	n.d.	tr	0.04	0.05
P_2O_5	n.d.	n.d.	0.35	n.d.	0.25	0.25
H_2O+	0.49	1.27	0.88	3.69	1.25	0.91
H_2O-	0.11	0.43	0.17	0.29	—	—
F	tr	—	—	tr	n.d.	n.d.
	100.11	100.10	100.50	100.81	99.78	99.38

1. Coarse porphyritic elvan, Praa Sands (Analysis I, p. 335, Phillips 1875).
2. Fine, cherty elvan, Mellanear, Hayle (Analysis III, p. 335, Phillips 1875).
3. Porphyritic elvan, near Praze, Carnmenellis (Analysis 11, Ghosh 1934).
4. Fluxion-banded elvan, Trelavour Downs, St. Austell (Ussher *et al.* 1909).
5. Porphyritic centre of elvan dyke cutting Tregonning granite, Tregonning Hill (*New analysis.* Analyst: M. Stone).
6. Fine-grained margin of elvan dyke cutting Tregonning granite, Tregonning Hill (*New analysis.* Analyst: M. Stone).

III. FIELD RELATIONS

1. **Relations to country rocks.**

Exposed contacts between granite and killas are always sharp, but often irregular and frequently complicated by apophyses from the granite or granite dykes cutting across the contacts. It seems probable that apophyses, sheets and dykes occur also at many unexposed contacts; this probability is emphasised by records from many mines (Hill and MacAlister 1906; Collins 1912; Dines 1956, pp. 85, 133, 137, 523, 580).

The Bouguer anomaly map (Bott *et al.* 1958) indicates, in general, that the granite contacts are steeper on the south side than on the north side. This is generally confirmed by the widths of the aureoles (Fig. 1). Roof zones are exposed over a small " plug " of granite at Porthmeor (Land's End), in a roof pendant at Rinsey Cove (Tregonning-Godolphin) and at Carpalla Clay Pit (St. Austell). The frequent proximity to the roof is indicated by the occurrence of granite at no great depth in many places; e.g., between the Carnmenellis granite and the ridge of Carn Brea (Hill and MacAlister 1906; Collins 1912; Davison 1930), the great extent of the aureoles on the northern sides of the Carnmenellis and St. Austell granites, which are confluent with the aureoles of several of the smaller masses (Fig. 1) and the intensity of tin mineralization which appears to be related to a series of granite ridges (Hosking 1962).

The Geological Survey One Inch Sheets clearly indicate that the strike of the Upper Palaeozoic rocks has, in many places, been affected by the granites. The swing in strike of the country rocks can be seen round the Land's End, Carnmenellis (eastern side) and Bodmin Moor granites. Ghosh (1934, p. 263) has stated that at three localities on the eastern side of the Carnmenellis granite " . . . . the intrusion has apparently obliterated the usual . . . . cleavages . . . . ; new cleavages and fold structures range themselves parallel to the periphery of the intrusion ". The effecs of granite emplacement are also shown by:

(a) deflection of the strike of greenstone masses, and

(b) the disposition of crush zones and associated slickensides (Ghosh 1934). Dearman and Butcher (1959) clearly show the arcuate strike of the Devonian and Carboniferous rocks of the north west border of the Dartmoor granite between the Sticklepath Fault and Sourton. Further south, between Sourton and Longford Quarry, the general strike is transgressed by the granite, but rocks close to the contact dip off the granite. These authors also show that earlier recumbent folds have been tilted by the emplacement of the Dartmoor granite.

The Mylor slates and their associated metadolerites in the Land's End aureole appear to dip off the granite. An S-plane which may correspond with S_2 of the Porthleven district (Stone 1962) and which tends to be flat-lying in regions away from the granites, dips off the Land's End granite at angles of 15 degrees to 20 degrees; i.e., roughly parallel to the contact (Floyd 1962).

2. **Relations between granites and regional structure.**

Several authors have indicated that emplacement of the granites was controlled by pre-existing anticlinal structures in the country rocks (Collins 1912; Hill 1913; Osman 1928; Robson 1945; Hosking 1962). Osman considered that the positions of the granite masses were related to the intersections of three separate fold systems and Robson concluded that the distribution of the granites could be explained by assuming that they were emplaced in domes which occurred at the intersection of east—west and north-east—south-west fold systems. In a cross section from near the Lizard to Davidstow, Hendriks (1937, Pl. 22) shows granite occurring in the cores of three successive anticlines.

However, in describing the Palaeozoic sedimentary rocks of western Cornwall, Hill (1901, p. 61) states that " . . . . they had suffered so much mechanical deformation that their original characters had been masked, and . . . . we can no longer depend upon the dip of the strata as a reliable index of stratigraphical relationship." Herein lies the main difficulty in relating granite emplacement to structures in the country rocks. Recent work in south Cornwall (Lambert 1959; Stone 1962) and in north Cornwall (Mackintosh 1963) shows that the fold patterns are complex and that there is a prominent flat-lying or low-dipping cleavage which itself is folded into gentle antiformal and synformal flexures. Similarly, the structures further east do not permit of an interpretation of simple upward-facing anticlines and synclines (Dearman and Butcher 1959; Simpson 1960). Further, there is evidence (Stone, unpublished) that the succession in the Porthleven district is the reverse of that indicated earlier (Flett 1946) and that the Mylor Beds are younger than the Gramscatho Beds. If this be the case, the concept of a simple anticline having a core of granite emplaced in Mylor Beds is untenable. It is clearly unwise at the present state of knowledge to relate granite emplacement to the structure of the country rocks until more is known about the relations between the small and large scale structures and the approximate positions of the time planes.

Evidence given earlier in this paper indicates that the granites reached their present positions by forceful intrusion which caused doming of flat-lying structures (Land's End, Dartmoor), transgression of structures (Tregonning, Bodmin, Land's End and Dartmoor) and apparently marginal folding and cleavage development (Carnmenellis). This evidence is inconsistent with the view apparently held by some authors (Collins 1912; Ghosh 1934; Hosking 1962) that the granites were emplaced into and moulded by pre-existing upward-closing folds in the country rocks.

3. **Internal features.**

(a) CONTACTS. In many places the margins of the granites are finer-grained than their interiors (Collins 1912; Reid *et al.* 1911; Davison 1930). This is especially true of some of the smaller intrusions (Davison 1930); e.g., elvan dykes which often exhibit a markedly "chilled" margin and the Carn Brea mass, which becomes finer-grained where the ridge narrows (Hill and MacAlister 1906). R. H. Worth (1903) regarded the Legis Tor felsite of Dartmoor as a typical "chilled" uncontaminated margin (see also Ussher 1912). On the other hand, other contacts are not "chilled". At the Burrator Quarry (Dartmoor), the coarse granite persists to the irregular, discordant contact with a "migmatitic" facies of the adjoining metapelites (Brammall and Harwood 1932). In the Land's End granite, the contacts at Porthmeor and at Wicca Pool contain the same type of porphyritic granite as that which occurs away from the contacts. At the former locality, however, apophyses from a porphyritic granite "plug" tend to be finer-grained than the "plug".

Cataclastic effects are observed at the eastern end of the Carnmenellis granite and in the Carn Brea ridge (Hill and MacAlister 1906; Ghosh 1934). In hand specimen, these effects are shown by a distinct foliation with which is associated crushing and mylonitization. Similar phenomena are recorded by Reid *et al.* (1910) from the margins of the Bodmin Moor granite.

(b) Relations between granite types

(i) *Major units.* At the beginning of the century, the Geological Survey recognised a fine-grained granite facies in the dominantly coarse porphyritic plutons. Since then, work by Ghosh (1927, 1934) on the Bodmin and Carnmenellis granites, by Osman (1928) and Jones (1963) on the Scilly Isles granite, by Brammall (1926) and Brammall and Harwood (1923, 1932) on the Dartmoor granite, by Richardson (1923) and Exley (1959) on the St. Austell granite and by Subbarao (1960) and Stone (1960) on the Tregonning-Godolphin granite has clearly indicated the composite nature of these plutons.

In eastern Dartmoor, Brammall and Harwood (1923) recognised four stages of granite emplacement. Stage 1 is now represented by relatively basic fine-grained biotite-microgranite, which occurs as rounded inclusions in the two succeeding stages. Stage 4 consists of late-stage dykes of aplite. Stages 2 and 3 are porphyritic biotite granites. Stage 2 is the " Tor " or " Giant " granite, which generally overlies Stage 3. The latter is the " Quarry " or " Blue " granite. This granite is exposed at the foot of Haytor Rocks, where it presents a sharp fine-grained contact (leucogranite facies) with the overlying coarse porphyritic " Tor " granite, but further north grades downwards into coarse porphyritic biotite granite. The latter differs mineralogically and chemically from the Stage 2 granite (Brammall 1926; Brammall and Harwood 1932). Generally, Stage 3 granite underlies or forms sill-like intercalations in the Stage 2 granite. This relation and sequence is similar to that proposed by Osman (1928) for the Scilly Isles granites.

In the Carnmenellis granite, Ghosh (1934) recognised three stages of intrusion of porphyritic biotite granite, which he called Types 1, 2 and 3. The earliest rock (Type 1) is, apparently, veined by Type 2. According to Ghosh, Type 3 also veins Type 1, but at one locality grades " dyke-like " into Type 1. Type 3 is assumed to be younger than Type 2 because it is more acid and contains a lower percentage of heavy minerals (Ghosh 1934). The authors are not convinced of the reality of the three separate granite types described by Ghosh. Recent work by Austin (1960) has indicated that the three types are merely local variants of a single porphyritic biotite granite and petrographic modal analyses by Chayes (1955) show that there is no significant difference between the modal data of Type 1 granite and Type 2 granite.

Similarly, recent detailed work on the Bodmin Moor granite (Exley, unpublished) has cast doubt on the validity of Ghosh's separation of " normal " and " Godaver " types (Ghosh 1927).

In the St. Austell granite, an arcuate junction between the porphyritic biotite granite (to the east) and the porphyritic lithionite granite is convex towards the former. This, together with the shape of the aureole and the pattern of the mineral lodes indicates that the porphyritic biotite granite was intruded first (Exley 1959).

On the other hand, the porphyritic lithionite granite grades westward into the non-porphyritic lithionite granite, patches of which also occur in the later fluorite granite.

The relations between the porphyritic and the fine-grained granites shown on the Geological Survey One Inch Sheets are variable. On Bodmin Moor, the contacts are sharp and the fine porphyritic biotite granite is said to be intrusive into the coarse porphyritic biotite granite which is veined by the former (Reid *et al.*, 1910). In the Carnmenellis mass, the fine-grained granite between Boswyn and Bolitho contains veins of coarser granite (Hill and MacAlister 1906). It also sends veins into the porphyritic granite (Type 1 of Ghosh), but at Crowan Beacon, there is a passage into porphyritic granite (Hill and MacAlister 1906; Ghosh 1934).

A " fine-grained " granite occupies the central part of the Scilly Isles granite pluton. Barrow (1906) states that there is generally a passage from fine-grained granite into the porphyritic granite, although both he and Osman (1928) refer to dykes of fine-grained granite which cut the coarse granite. Both authors consider that the fine-grained granite is later and intrusive into the porphyritic granite. Osman (1928) further considers that the fine-grained granite was intruded as a sheet, comparable with the Stage 3 granite sheet of eastern Dartmoor (Brammall and Harwood 1923).

Whilst the majority of authors appear to have considered that field relations indicate that the fine-grained granites are later than the porphyritic rocks with which they are associated, Davison (1930) states that they are of approximately the same age, since there is often mutual penetration of the two types.

(ii) *Minor intrusions.* Dykes and veins of aplite (sometimes associated with pegmatite), felsite, microgranite and quartz and granite porphyry cut the major intrusions and the country rocks. Occasionally, stringers and veins of pegmatite and lumps of aplitic material (" felsite " and microgranite) occur within the major intrusions.

a. Aplite Dykes.

Aplite dykes in the Carnmenellis granite were described by Stone and Austin (1961) who divided them on petrological grounds into three types and also described examples in which dyke margins were penetrated by potash feldspar megacrysts from adjacent porphyritic granite. The present authors have observed similar phenomena on Dartmoor, Bodmin Moor and in the Scilly Isles.

Many of the minor intrusions in the granites appear to be controlled by joints, though not necessarily the predominant joints (see e.g. Brammall 1926A, 1926B). Osman (1928) has described aplites intruded along joints in south-east St. Mary's (Scilly). Here, a joint-controlled aplite spreads out as a sheet where it meets a thrust plane. Clearly, the generally sharp contacts and parallelism of the margins of the aplites together with the dilatational phenomena observed at Porthmeor and Tremearne point to forceful injection rather than exudation of aplitic material from porphyritic granite into joints as a means of emplacement.

b. Pegmatites.

Many of the smaller pegmatites, especially those occurring at Porthmeor and in the Tremearne sheets are intimately associated with aplite. Indeed, there is a complete gradation from aplite through pegmatite containing lumps of aplite to pegmatite with small patches of interstitial aplite. Such relations are suggestive of metasomatism and recrystallization (see below, Section IV). It is also likely that pegmatite patches and streaks in many of the granites and the pegmatite margins or centres of many aplite dykes (e.g., Cape Cornwall, Porthmeor) can be interpreted as recrystallization (and probably also metasomatism) of the " host " rock to pegmatite in regions where volatiles have concentrated.

c. Elvans.

The general trend of the elvans is about N.N.E.—S.S.W. although there is a good deal of variation in the strike. There is a marked parallelism between the trend of the elvans and that of the main mineral lodes. Where the mineral lodes show anomalous trends, so also do the associated elvans.

The late granite-porphyries are clearly intrusive and post-date the coarse porphyritic biotite granites and the porphyritic and non-porphyritic lithionite granites; e.g., Trelavour Downs (St. Austell) and Tregonning Hill, but the relations to the fine porphyritic biotite granites are not clear from the Geological Survey maps or from the descriptions in the Memoirs. Reid *et al.* (1911) suggest that "soft" elvans in eastern Bodmin Moor are the upward extensions of the finer (fine-porphyritic) granite and that they are possibly later than the normal harder elvans. However, they provide no evidence. Ghosh (1934) indicates that the elvans (and aplites) were emplaced after his Type 3 granite; i.e., subsequent to the emplacement of Type 1 and its associated fine porphyritic biotite granite. Elvans (shown on the Geological Survey Sheet 352) cut all of the granite types described by Ghosh except the fine granite.

Clearly there is considerable variation in the petrological and chemical characters of the elvans and it is possible that different types or even similar types have been emplaced at slightly different times. Certainly, an earlier set of elvans is indicated by inclusions in the Dartmoor granite (Brammall 1926A) and proved by an elvan, illustrated by Hall (1930, Fig. 4A), which is cut by a sheet of non-porphyritic lithionite granite on the wave-cut platform west of Legereath Zawn (Tregonning granite). Another elvan occurs as a large xenolith close to the roof of the Tregonning granite, near Rinsey. An account of these elvans will form the subject of another paper by one of us (M.S.).

(iii) *Flow structures and joints.* " Flow " structures are due to the alignment of the long axes of megacrysts of potash feldspar. In many places there is also a planar orientation of (010) faces of these crystals. However, difficulty in measuring this alignment is frequent, especially when individual megacrysts lie oblique to joint surfaces. To place observations on a more rigorous basis requires random measurement of many individuals from each locality. Estimates of a general direction of alignment based on an overall view of an exposure may become subjective when the alignment is only moderate or poor.

Brammall (1926A, p. 261) states that, " Except near the granite margin flow-lines are rarely so good or so concordant over a large exposure. Divergence from a very local ' mean ' trend . . . . is considerable ". Ghosh (1934, p. 271) considers that the " . . . . behaviour of the main and minor flows of the three granite types [of the Carnmenellis mass] indicates movements practically independent of a directed crustal pressure ". Reference to his map (Fig. 10, p. 269) hardly supports this contention. Nor indeed do his own data support his suggestion that the pitch (more correctly called plunge) of the "flow" structures is steeper near the margins. Elsewhere, however, the plunge of the "flow" structures frequently appears to be steeper near to the margins of the plutons, as at Wicca Pool (Land's End).

The overall pattern of the "flow" structures and the main joints has been summarised by Exley (1959). This pattern clearly indicates an alignment of potash feldspar megacrysts in a northerly to north-north-westerly direction. S-joints are aligned parallel to the "flow" direction while Q-joints are nearly perpendicular to this and roughly parallel to the belt of mineralization.

From the data available, we tentatively conclude that the major joints and "flow" structures are part of a regional tectonic pattern related, not to the cooling or flowage of magma passively filling anticlinals in the country rocks, but to the forceful emplacement of a granite mass (solid, liquid or both) under a regional stress pattern.

Space does not permit a discussion of the interesting joint patterns (particularly the "bedding") in the granites described by Brammall (1926A), Osman (1928) and Ghosh (1934). Suffice it to say that the "bedding" observed in the roof zone of the Tregonning granite; e.g., at Trewavas Head, is controlled by rock fabric (alternating leucogranites, aplites and tourmaline granites) as it is also in the St. Austell granite (Exley 1959), thus supporting Brammall's statement that " The possibility that bedding could progressively conform to evolving topography may be dismissed as remote. It is more probable that bedding has been an important factor in moulding the topography, ... ". (Brammall 1926A, p. 261).

IV. PETROGENESIS

Evidence has been presented above which indicates that the granites of south-west England were forcibly emplaced into their present positions. The orientation of the potash feldspar megacrysts points to some measure of flowage. However, neither of these features is necessarily consistent with the flowage of a largely liquid magma. The local occurrence of sheared margins to the plutons and frequent textural evidence such as strain shadows in quartz, the granulation of quartz marginal to megacrysts of potash feldspar (as at Greator Rocks, Dartmoor) and bent grains of plagioclase are indicative of a large component of solid flow, aided no doubt by interstitial " mineralizing " solutions, for which there is abundant evidence. The action of these solutions in aiding recrystallization and migration of materials may well have obliterated other evidence for solid flow. The high tectonic level of these plutons, the comparatively low metamorphic grade of many of the inner aureole rocks and the general absence of associated migmatite facies provide additional evidence that these granites were almost "dead" when they were emplaced (Read 1957, p. 337). However, a close study of their field relations (particularly the small-scale relations), together with their textures, mineralogy and chemistry can lead to reasonable inferences regarding their former history and the mechanisms responsible for their variations. In this section, we propose to assemble and examine evidence which leads towards a unity of the phenomena observed in the field and thin section and the experimental work on the " granite system ".

1. **Metasomatism and recrystallization.**

Several lines of enquiry lead to the conclusion that the present fabric of the rocks considered here is the result of recrystallization accompanied in many instances by metasomatism (Stone and Austin 1961; Stone 1963). From a comparison of the mineralogy of extrusive and plutonic rocks of "granitic" composition, Tuttle (1952) suggested that unmixing of a single alkali feldspar might eventually result in the production of separate grains of two feldspars—a potash-rich feldspar and a plagioclase feldspar, Tuttle and Bowen (1958) classify granites which contain these two feldspars as *subsolvus granites.* These authors believe that whilst many subsolvus granites do not have a fabric which resulted from crystallization from magma, this does not preclude a magmatic origin for the rock. In discussing a photomicrograph of a Colorado granite in which microcline is interstitial to quartz and plagioclase, Tuttle and Bowen (1958, Pl. 6, Fig. 2, and pp. 141-142) state " Many geologists would perhaps call this a metamorphic rock, but the general field relations plus the fact that it contains approximately equal amounts of plagioclase, microcline and quartz strongly suggest that this is a normal magmatic granite which has experienced considerable recrystallization in addition to the unmixing of the feldspars ".

An outline of the field, textural and some chemical evidence for the metasomatic origin of the present fabric of the coarser granites of south-west England follows.

(a) FIELD RELATIONS

Examples of evidence for the late growth of big potash feldspars in both pegmatite and coarse porphyritic biotite granite have been described by Stone and Austin (1961). A particularly good example of a megacryst of potash feldspar crossing the junction between a later aplite (which had produced dilatation) and an earlier banded granite and aplite was figured and described from the Tremearne sheets. Since then, two further examples of big potash feldspars penetrating deeply into adjacent pelitic hornfels have been observed at Tremearne. Megacrysts also cut across bands in aplite and where the transgression is oblique to the banding no offset is observed. Sometimes, however, the bands are bent as though they had been pushed by the growing megacryst. Such phenomena have been explained in other ways (see e.g. Staatz and Trites 1955; Orville 1960), and clearly the whole problem is tied up with the nature and origin of the banding—a project at present under investigation by one of us (M.S.).

Further evidence for recrystallization and replacement is provided by pegmatite-aplite relations. At Tremearne. there is every gradation from aplite with or without patches or streaks of pegmatite, through stages in which aplite occurs as inter-connected and disconnected irregularly-shaped " lumps " in pegmatite, to pegmatite which contains mere relicts of interstitial aplite. Similar, but more extensively exposed examples showing the same sequence of events have been described from the Sardloq area of S.W. Greenland by Windley (1963). Uspensky (1943) has also described the pegmatitization of aplite from the Transbaikal region of the U.S.S.R. He indicates that the process was essentially one of recrystallization with little or no metasomatism. However, preliminary modal data from Tremearne show that the coarser rocks are always richer in potash feldspar than their associated finer-grained rocks (Stone, unpublished) and since the former have replaced finer-grained material, metasomatic exchange must have occurred. No convincing evidence has been observed to suggest a process of grain reduction, i.e., aplitization, such as has been described from many pegmatite areas in the U.S.A. (Jahns 1955, p. 1102).

The field evidence for the metasomatic growth of potash feldspar megacrysts in the coarse porphyritic biotite granites includes:

(a) the occurrence of megacrysts projecting from porphyritic granite into aplite;

(b) the passage of aplite along the strike and sometimes laterally into porphyritic granite; and,

(c) the occurrence of megacrysts in pelitic hornfels inclusions in the porphyritic granites. (Stone and Austin 1961).

The occurrence of big potash feldspars astride aplite-porphyritic granite contacts has also been observed by us on Dartmoor, Bodmin Moor, and in the Scilly Isles. Some aplite dykes clearly cut across big feldspars; the latter terminate abruptly against the aplite. Such dykes may belong to a later generation; evidence from Tremearne, referred to earlier (p. 156), indicates at least two generations of aplite there.

It could be suggested that the aplites represent material which has " drained " from the granite into joints and that the comparatively few big feldspars observed transgressing the contacts were due to irregularities of the joint surfaces, whilst others were caught up in the aplite as xenocrysts. Against this suggestion, however, are three factors:

(i) many aplites provide evidence for distinct dilation (e.g., Tremearne, Porthmeor), and must have been emplaced by forceful injection;

(ii) the occurrences of aplite dykes which cross granite/country-rock contacts imply at least some upward or lateral movement of aplitic material;

(iii) textural evidence (see below) indicates later growth of megacrysts which penetrate aplite.

This is not to say that the aplites have not been derived from their local granites; indeed this source is most likely since the alternative would involve postulating a later aplite magma reservoir.

The occurrence of megacrysts of potash feldspar in pelitic xenoliths has been noted by us in all the main granite masses, except that of the Scilly Isles, and has been cited by many authors describing other occurrences as evidence for their metasomatic origin (see Read 1957). In his later work, Read doubts the significance of the " dents de cheval " since he finds evidence for the mechanical mixing of magma and " pasty " country rock in high level plutons in South Africa (Read 1957, pp. 349-350). Although " softening-up " of pelitic xenoliths is to be expected in the granitic rocks considered here, there is no evidence to suggest mechanical admixtures and original bedding is frequently seen (Brammall and Harwood 1923).

Potash feldspar megacrysts are not confined to the granite and pelitic xenoliths, but occur also in the early microgranite (Stage 1 of Brammall and Harwood 1923; 1932) and in " lumps " of aplite or felsite.

Flowage lines marked out by the long axes of potash feldspar megacrysts are sometimes deflected by " felsite " or microgranite inclusions which may contain several randomly-oriented megacrysts of the same mineral. This is considered to offer further evidence of flowage (which presumably was synchronous with the growth of the alkali feldspars) in solid or nearly solid rock.

(b) TEXTURAL RELATIONS

We are fully aware of the difficulties encountered in interpreting textures observed in thin section and as a result we would tend to place more weight on field, chemical and experimental evidence if these were markedly at variance with the textural evidence. However, the interpretation of the textures of the granitic rocks considered here appears to harmonize with other data and with the conclusions of Tuttle and Bowen (1958) referred to above.

Unfortunately, little detailed study of the textures of these granites appears to have been published. Most of the brief account which follows is based upon our own work on Bodmin Moor, St. Austell, Tregonning-Godolphin and a cursory examination of thin sections of the Dartmoor granites, and on Austin's (1960) work on Carnmenellis.

Quartz

Two " generations " of quartz can be recognised in many of the granites:

(i) Large (millimetre-grained) individuals which provide evidence for two or more growth stages (Fig. 2) are comparable with porphyroblastic quartz which has grown in basic inclusions (Brammall and Harwood 1932, Fig. 15).

(ii) Smaller ($<$0.1 mm. to 0.5 mm. across) grains, which form interstitial aggregates (along with plagioclase) to the larger components of the fabric or are included in plagioclase and potash feldspar. After allowing for some reduction in size upon inclusion, the quartz inclusions shown in

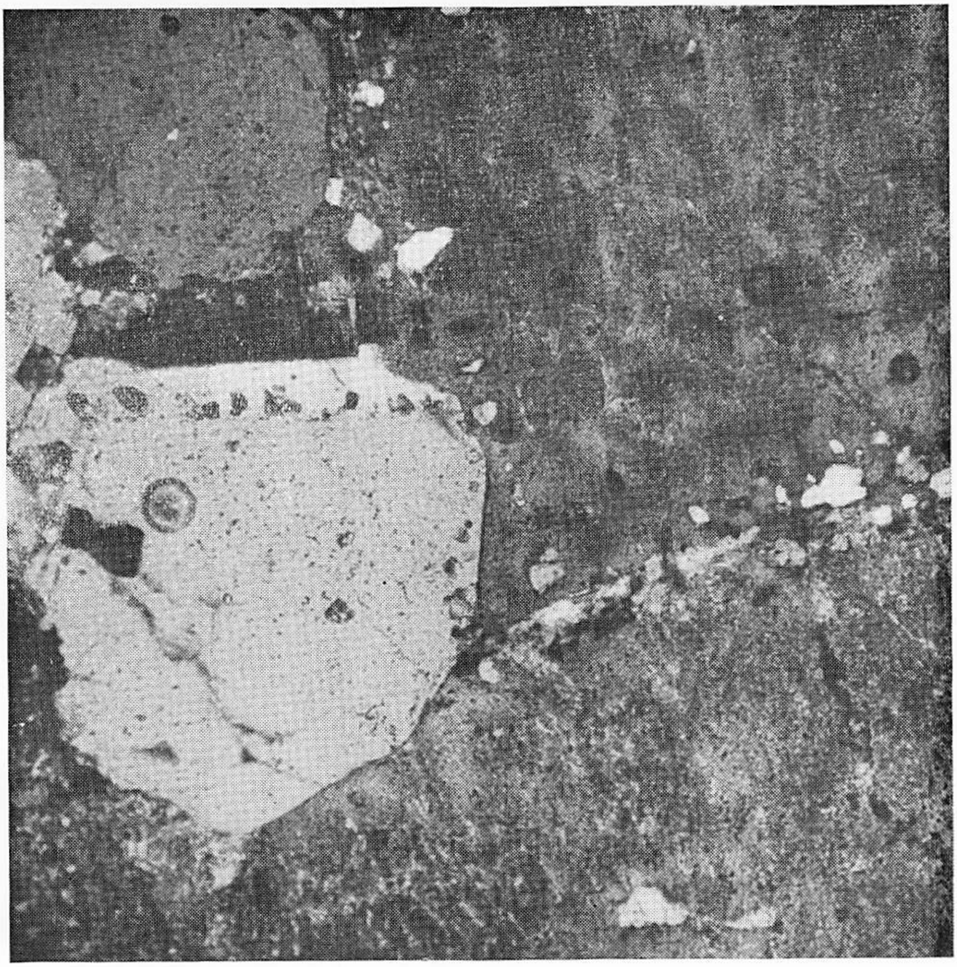

FIG. 2. Photomicrograph of a fine-porphyritic biotite granite (Godolphin Hill) showing a subhedral quartz grain with marginal inclusions of potash feldspar and parts of two megacrysts of potash feldspar, which occupy most of the field. A narrow rim of small quartz and plagioclase grains occurs between the two megacrysts and a zone of similar material is included close to the edge of the megacrysts on the left. (X 60).

Fig. 2 could not exceeed 0.2 mm. in diameter. Whether these grains have undergone a reduction in size prior to inclusion or represent an " early " grain size which has been incorporated in the growing alkali feldspar is not certain.

Potash feldspar

In the porphyritic granites and pegmatites, potash feldspar frequently includes quartz and plagioclase grains. Quartz occurs as rounded to six-sided inclusions and sometimes occurs in a marginal zone (see above). The edges of the " euhedral " alkali feldspar megacrysts are often, in detail, irregular in outline, with lobate margins and amoeboid prolongations which penetrate between the adjacent grains of the groundmass.

Patches of optically continuous plagioclase (albite) included in the potash feldspar are frequently also in optical continuity with the perthite lamellae and have resulted presumably from exsolution. Occasionally however *two* sets of optically continuous albite patches are found in a single host crystal in the lithionite granites and leucogranites of the Tregonning-Godolphin mass. One of these sets is in optical continuity with the perthite lamellae and is interpreted as exsolution albite, while the other is not so related to the perthite lamellae and must represent the undigested fragments of a plagioclase grain which has been replaced by potash feldspar (Fig. 3). Megacrysts of potash feldspar which project into aplite sometimes include a zone of fine-grained aplite parallel to the projecting crystal faces (Stone and Austin 1961, Pl. 1). Examples from the pegmatites at Tremearne include patches of aplitic matrix.

Plagioclase

In most of the granitic rocks, plagioclase is the most euhedral component of the fabric of the major constituents. Where its composition is not close to pure albite it is generally zoned. These features might be taken to indicate a magmatic origin, but other features must also be considered:

(a) Where the anorthite content of the plagioclase does not exceed about An_{30} it is likely that a single feldspar crystallized at high temperatures and subsequently unmixed to form plagioclase and alkali feldspar (Tuttle and Bowen, 1958). However, other factors which stabilize the initial crystallization of two coexisting feldspar phases have to be taken into consideration, such as the effects of volatile constituents other than water; e.g., fluorine (Wyllie and Tuttle 1961), but until more is known about factors which can be used to estimate the partial pressures of these constituents in nature, the extent to which the solidus-solvus gap may be closed in the system ($KAlSi_3O_8$—$NaAlSi_3O_8$—other constituents) will remain little more than a guess. No doubt further work on the partition of F and (OH) in coexisting topaz, tourmaline and lithionite and tourmaline and biotite will lead to estimates of the relative partial pressures of F and (OH).

(b) Plagioclase megacrysts in some metasomatised hornfelses and migmatites are euhedral and zoned, such as those described from the Leinster granite aureole by Coe (1958).

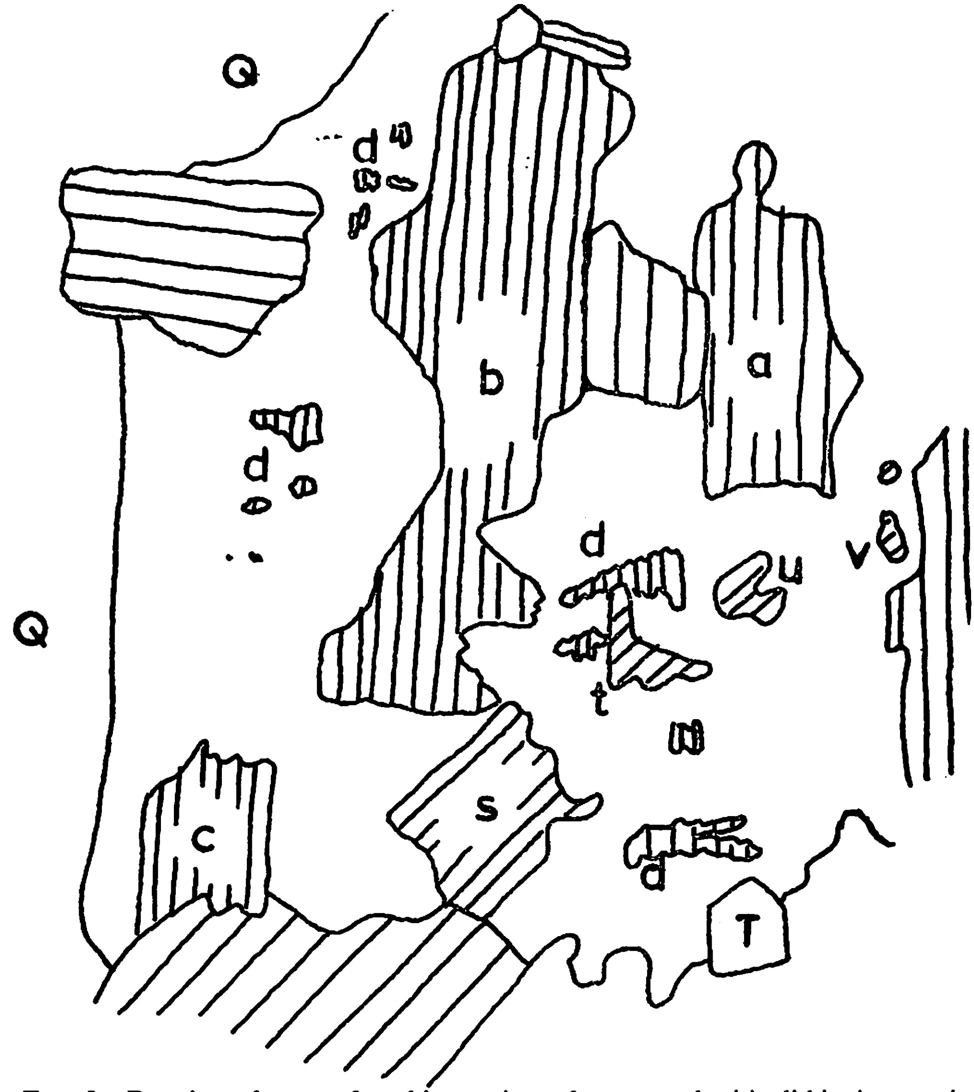

FIG. 3. Drawing of part of a thin section of non-porphyritic lithionite granite (Tregonning granite) showing two kinds of optically continuous albite inclusions in potash feldspar. Grains a, b and c are inclusions of albite which are optically continuous with one another and with perthitic patches of albite (labelled d). This set of inclusions is believed to have resulted from the unmixing of a homogeneous alkali feldspar. Grains s, t, u and v are also optically continuous with one another but not with the perthitic patches. These grains are interpreted as the relicts of a grain of albite which has been partially replaced by alkali feldspar prior to the unmixing of the latter. Clear unlabelled areas = single grain of potash feldspar. Q = quartz; T = tourmaline.

Mica

Evidence for a " xenolithic " origin of much or all of the biotite in the biotite granites is provided by the occurrence of all stages from recognizable xenoliths, through biotite-rich xenoliths having biotitic streaks which pass into the granite, to biotite " clots " (so-called basic segregations) and isolated grains (Stone and Austin 1961). Such an origin is implied in any case if these rocks have their origin in palingenesis (Brammall and Harwood 1932; Lacy 1960).

Lithionite and muscovite are frequently in optical continuity with skeletal networks of these minerals in potash feldspar. This is clearly a texture which indicates the replacement of potash feldspar by mica and implies that these micas developed at a late stage of recrystallization.

Tourmaline

Brammall and Harwood (1925 p. 321) indicate that " . . . . very little of the tourmaline can be described with absolute certainty as primary (pyrogenic) . . . ". The evidence from the Dartmoor granite presented by these authors is replicated in all the other granite masses. For example, prisms of tourmaline in the fine porphyritic biotite granite of Godolphin Hill are optically continuous with skeletal networks of this mineral in megacrysts of potash feldspar. The problem of tourmaline genesis is further discussed in Section VI of this paper.

Topaz

This mineral occurs predominantly in the lithionite granites and their associated minor intrusive phases. Occasionally it includes relict optically continuous " islands " of potash feldspar (as in the lithionite granites in the Tremearne sheets). It is nearly always separated or nearly separated from adjacent potash feldspar by a " reaction " zone consisting of minute grains of quartz.

* * *

Thus, textural relations indicate that in a number of places, the bulk of the present rock fabric has been superimposed upon and has largely or wholly obliterated traces of an earlier fabric. This earlier fabric may well be represented by that which occurs as inclusions in the larger grains, the " aplitic " matrix of some of the coarser granites (e.g., Type 3 granite of Carnmenellis; see Austin 1960, p. 74 and Fig. 38) and pegmatites, and the lumps of aplite[1] which occur within pegmatites (Stone and Austin 1961). Although the aplitic rocks reveal some evidence for metasomatism and recrystallization, they would appear to be the least modified of all the granitic rocks. If the origin of these granites lies in crystallization from magma, as evidence presented later indicates, the " aplitic " fabric would correspond more closely, presumably, with the initial products of crystallization than any of the other rock fabrics. At the same time, it must be noted that in some outcrops; e.g., Bodmin Moor, St. Austell, Land's End, relicts of an " aplitic " fabric have not

[1] This excludes the markedly banded aplites (line rocks) which are associated with pegmatite at Tremearne. Work on these rocks is at present in progress.

yet been identified, although the replacement origin of much of the existing fabric can scarcely be doubted. For the moment, it therefore remains an open question whether the aplite-granite relations of Carnmenellis, Tregonning-Godolphin and parts of Dartmoor are a local phenomenon or whether recrystallization has obliterated them in the other granites.

(c) CHEMICAL EVIDENCE FOR METASOMATISM

Metasomatic exchange of material (particularly alkalis) between xenoliths and granite and between wall rock and granite is revealed by the chemical data of Brammall and Harwood (1932), Ghosh (1934) and Bowler (1958). Bowler has demonstrated a marked enrichment in alkalis (including Rb and Cs) and fluorine in the pelitic hornfelses adjacent to the Tremearne sheets, and clearly material was capable of migrating short distances into the wall rock and xenoliths. Field and textural evidence from within the granites suggest internal metasomatism; i.e., autometasomatism.

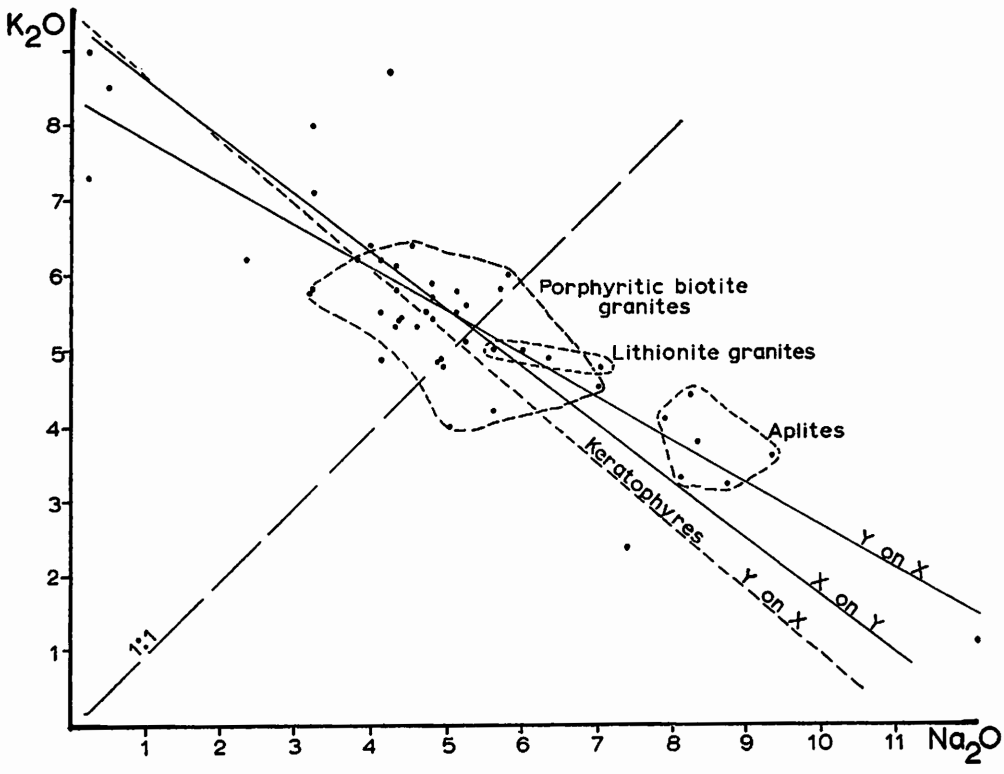

FIG. 4. Plot of molecular quotients (X 100) of K_2O (Y) and Na_2O (X) of 49 analysed granitic rocks from south-west England. Linear regression curves of Y on X and X on Y are shown by solid lines. Short dashes show the regression curve of K_2O (Y) on Na_2O (X) calculated from keratophyre data given by Battey (1956). The line showing equimolecular proportions of K_2O and Na_2O is shown by long dashes.

Metasomatism on a larger scale is difficult to demonstrate and will be discussed further after the effects of assimilation and magmatic differentiation have been considered. The relations between the major alkalis are indicated in K_2O—Na_2O diagrams like those given by Brammall and Harwood (1932, Fig. 2), Ghosh (1934, Fig. 4) and Stone (1960). Lines fitted to the points in these diagrams by regression analysis has good correlation coefficients (Stone 1961); the regression lines for the bulked data (48 analyses) are shown in Fig. 4 and the regression equations are:

(i) $(K_2O) = -0.575\ (Na_2O) + 8.33$

(ii) $(Na_2O) = -1.289\ (K_2O) + 12.06$

The correlation coefficient is -0.87 with 95 per cent confidence limits at -0.78 and -0.92. The figure clearly shows that the bulk of the porphyritic biotite granites have a K_2O/Na_2O ratio greater than 1 : 1, whilst the field of aplites (which includes the leucogranite, Table 7 (column 2)), lies well below the 1:1 line. A regression line (K_2O on Na_2O) of Battey's data (Battey 1954) on potash metasomatism (internal metasomatism) in New Zealand keratophyres is shown for comparison: this has a slope of —0.87 (compared with —0.58 for the equivalent curve fitted to the south-west England data) and a correlation coefficient of —0.94. Stone (1961) concluded that the inverse relations between the major alkalis was evidence for metasomatism and attributed the difference in slope between the granite data and the keratophyre data (which lie close to the " ideal " curve for the replacement of albite by potash feldspar) to the effects of assimilation in the granites.

However, conclusions based upon alkali data from granitic rocks are open to some criticism. In granitic rocks generally, the total alkali content is largely governed by the feldspar content. Since the majority of granites contain about 30 per cent of quartz (a constant!) and feldspar forms the bulk of the remaining 70 per cent, as one feldspar diminishes the other, in general, will increase. Thus, there is a tendency for K_2O to vary inversely with Na_2O irrespective of the processes causing variation and hence the variables considered are not wholly independent. On the other hand, Fig. 4 shows that the alkali sum is not a constant and that, as Na_2O increases in the later (uncontaminated) terms, total alkalis increase.

2. **Assimilation.**

Convincing evidence for the modification of the initial Dartmoor " magma " by assimilation has been presented by Brammall and Harwood (1923, 1932) and similar evidence was found in the Carnmenellis granite by Ghosh (1934). The main arguments are as follows:

(a) If the felsites (of Dartmoor), which are soda-rich, represent initial magma, the potash-rich nature of the granite can largely be ascribed to assimilation of shales.

(b) Aureole shales have a K_2O/Na_2O ratio considerably greater than unity, while in hornfelsed shale this value is close to or less than unity, implying the addition of Na_2O to the shales and the addition of K_2O to the granites.

(c) Pelitic hornfels minerals, such as cordierite and andalusite, occur as accessory minerals in the granite.

(d) Evidence for the disintegration of xenoliths and streaked-out trails of biotite from some of the xenoliths have been observed.

The implications of these arguments are that the uncontaminated rock has received K_2O, femic constituents and Al_2O_3 from pelitic xenoliths, and femic constituents and Al_2O_3 from the basic inclusions. Further, the high K_2O/Na_2O ratio but low total alkalis of contaminating pelites could account for the low angle of slope in the K_2O—Na_2O diagram (Fig. 4).

3. **The rôle of magma and magmatic differentiation.**

We have purposely avoided directly implying that magma played a part in the genesis of the granitic rocks of south-west England for the simple reason that neither observations in the field nor examination of textures can, by themselves, justify such an implication. The field evidence that might suggest crystallization from magma is found partly in the " chilled " contacts and the finer-grained nature of the smaller intrusions, and partly in the wedge-like nature of some of the apophyses at the rare exposures of granite-killas contacts. However, conclusions reached above have indicated that increase in grain size is related to late-stage recrystallization and metasomatic processes which are presumably governed in large part by the nature and behaviour of late-stage fluids.

The only other evidence that appears to indicate crystallization from magma comes from relating the compositions of granitic rocks to the experimental " granite system " (Tuttle and Bowen 1958; Yoder *et al.* 1957). Tuttle and Bowen (1958 p. 80) summarize by stating that " . . . . the compositional variation of the analyzed rocks containing 80 per cent or more albite + orthoclase + quartz are so closely related to the thermal valley on the liquidus surface of the system $NaAlSi_3O_8$—$KAlSi_3O_8$—SiO_2 that there is little doubt that crystal $\rightleftharpoons$ liquid equilibria are involved in the origin of the bulk of the granites ".

Normative and modal data available from Dartmoor, Bodmin Moor, St. Austell, Carnmenellis, Tregonning-Godolphin and Land's End are plotted in relation to the experimental " granite system " in Figs. 5 and 6. Included in these diagrams is the contour representing the highest concentration (5 per cent contour) of 571 analysed plutonic rocks in Washington's tables which contain 80 per cent or more normative Ab + Or + Q (from Fig. 42, p. 79, Tuttle and Bowen 1958).

Clearly, a large number of the analysed granitic rocks of south-west England lie close to the contoured maximum and it is considered that the reasoning of Tuttle and Bowen applies here also. However, the least contaminated (and probably also the least recrystallized and metasomatized) rocks are the " felsites " of Dartmoor and other leucocratic fine- to medium-grained terms. These rocks plot closer to the albite apex of the triangle than the porphyritic granites. It is suggested that the field outlined by the felsites, aplites and leucogranites corresponds with a " ternary minimum " of the natural granite system. This would almost certainly differ from the minima in the far simpler experimental system since other constituents, not included in the experimental work, are present in the natural system. The difference in position between the " felsite " field and the porphyritic granite field can now be attributed either to assimilation or to magmatic differentiation or to both processes.

We now turn to the problem of magmatic differentiation.

The majority of petrologists who have worked on the granites of south-west England appear to have assumed that the granites were emplaced as magmatic rocks and have attributed their variation to magmatic differentiation, modified in many instances by the effects of assimilation (Brammall and Harwood 1932; Ghosh 1927, 1934; Exley 1959).

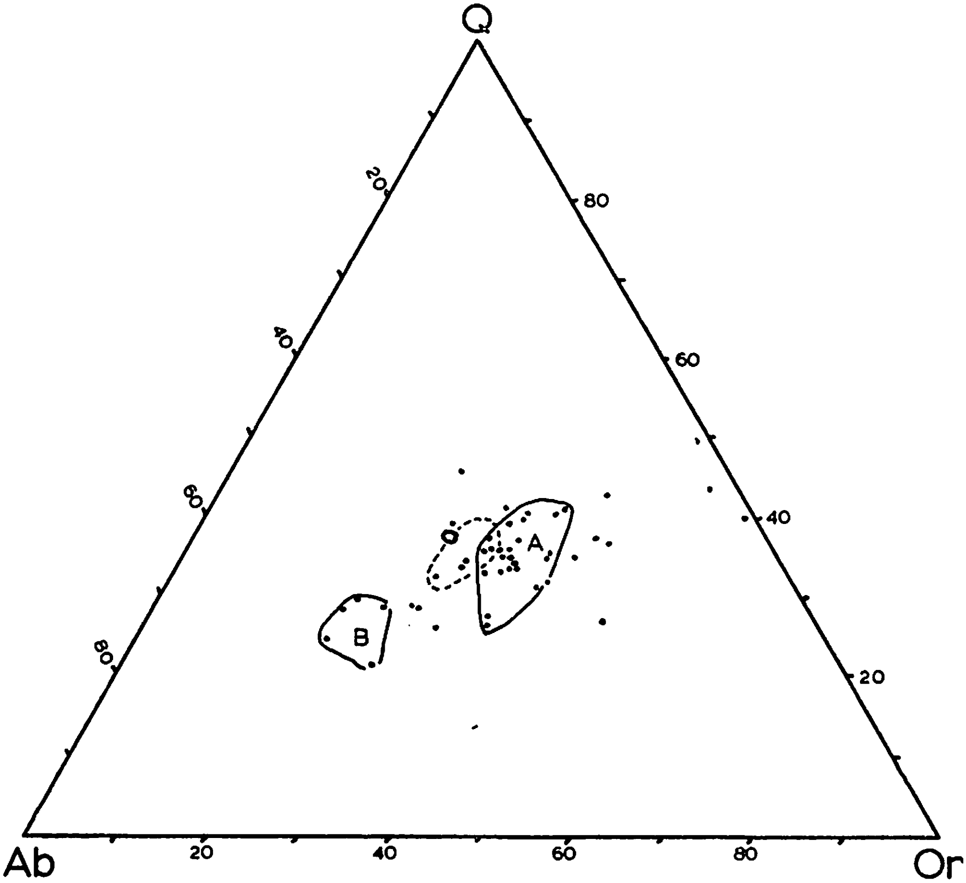

FIG. 5. Plots of normative data (molecular norms) of 46 analyses of granitic rocks of south-west England on a Q (quartz) — Ab (albite) — Or (orthoclase) diagram. The 1000 bar P_{H_2O} ternary minimum of the experimental "granite" system is shown as a circle and the highest concentration of plutonic granitic rocks (Tuttle and Bowen, 1958) is shown by a dashed line. Field A = field of coarse- and fine-porphyritic biotite granites. Field B = field of early felsites of Dartmoor and aplites of Tregonning—Godolphin and Meldon. (Sources of data: Ghosh 1927, 1934; Brammall and Harwood 1932; this paper).

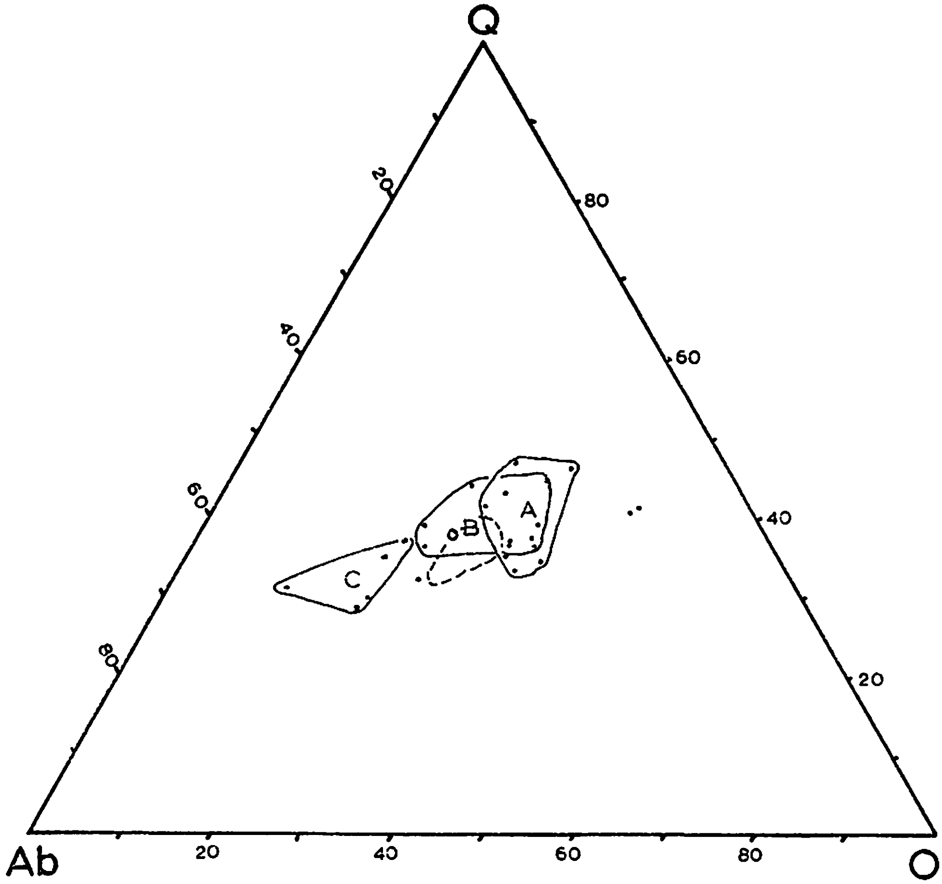

FIG. 6. Plots of modal data from Tables 3, 5 and 7 of this paper on a Q-Ab-Or diagram. Circle and field included in dashed line as in Fig. 5.
Field A = field of coarse-porphyritic biotite granites.
Field B = field of fine-porphyritic biotite granites.
Field C = field of aplites.

The occurrence of points on a smooth curve in a variation diagram is usually regarded as suggestive of magmatic differentiation: such a curve is shown by those rocks which represent most closely the liquid line of descent—the glassy rocks (Bowen 1928, p. 94). Plutonic rocks, however, are both coarser-grained and likely to plot away from the points lying on the true liquid line of descent. While Ghosh (1934, p. 252) states that the " scattering of points " (shown in his Fig. 2) is " a feature characteristic of a differentiation series " he nevertheless attempted to draw curves through these points. Brammall and Harwood (1932 Fig. 1, p. 175) likewise show complex differentiation trends through a scatter of points. Where a scatter of points occurs (as it tends to towards the acid end of the variation diagrams for glassy rocks), the only line that can properly be drawn is one computed from the data, and it would seem in the cases quoted that the data as presented are insufficient to draw firm conclusions. Clearly, there is no convincing case here for or against magmatic differentiation. Indeed, it may be difficult to relate a particular process to variation based upon data summed to a constant (Chayes 1962).

Perhaps the broad trend of soda, lithia and volatile enrichment indicated by the work of Brammall and Harwood (1932), Ghosh (1934), Exley (1959) and Stone (1961; 1963) is the result of magmatic differentiation. The goal of all granitic magmas, whether primary or resulting from the contamination of a palingenetic " felsite " magma is the ternary minimum in the " granite system ". Brammall and Harwood (1932, pp. 199, 223) gave it as their opinion that the *initial* Dartmoor magma was probably soda-rich, evidence being provided by the felsitic " chilled " margin near Legis Tor and the initial enrichment of pelitic xenoliths in Na_2O. On the other hand, the *later* terms (aplites and leucogranites) in the Tregonning-Godolphin granite are also soda-rich. Available data indicate that both these early and late terms plot close together in the Q-Ab-Or diagram and their plots define the field of the assumed natural " ternary minimum " (Fig. 5). The early soda-rich terms are interpreted as indicating an early, almost uncontaminated magma, presumably representing an approach to the composition of the initial liquid generated during palingenesis; the late soda-rich terms are interpreted as the final " differentiate " from the contaminated magma.

Thus, differentiation appears to be consequent upon contamination, as was concluded by Brammall and Harwood (1932), whilst the effects of local potash metasomatism have been superimposed upon the results of both differentiation and contamination. Metasomatism is revealed mainly by field and textural relations, magmatic differentiation only by the chemistry of the rocks. However, a further phenomenon which could mask the evidence for magmatic differentiation is large-scale " metasomatic differentiation ".

4. **Large-scale alkali transfer.**

Recent experimental work by Orville (1963) and similar work noted by Tuttle and Bowen (1958) and Mackenzie (1960) has demonstrated the rapid transfer of alkali ions between feldspar and vapours containing alkali chloride at *ca.* 660 degrees to 630 degrees C. and 2000 bars P_{H_2O}. Thus arises the possibility of extensive ion exchange of alkalis in the presence of vapours which will dissolve considerable amounts of alkali. Earlier work by Orville (1960) on the Black Hills pegmatites in Dakota had indicated that the pegmatite fraction of the Buell Ranch Complex, which lay close to the ternary minimum of the experimental system, represented the last fraction of the aplite-pegmatite magma to crystallize, while the bulk composition of the aplite and pegmatite lay near the quartz-feldspar field boundary to the sodic side of the pegmatite (Orville 1960, Fig. 10). In the light of Orville's experimental work (Orville 1963) and observations which suggest replacement of aplite by pegmatite at Tremearne (Stone 1960; Stone and Austin 1961), we suggest that the bulk composition of the aplite-pegmatites of the Buell Ranch Complex represents an initial rock which has undergone metasomatic differentiation to produce a pegmatite above (richer in potash feldspar) and an aplite beneath (richer in albite). Modal data from Tremearne which suggest that such metasomatic differentiation has taken place here are to be published later by M.S.

It is possible that metasomatism of this type could occur over larger areas and it remains in the future to investigate the relations between larger components of granite complexes with metasomatic differentiation in mind. This type of differentiation could produce sharply contrasted rock types (which would lie on a straight line in the K_2O—Na_2O diagram) whose contacts would be gradational unless disturbed by subsequent mobilization. Gradational contacts have, of course, been described by several workers from the granites of south-west England; e.g., Scilly Isles, Carnmenellis, St. Austell (see Section III of this paper on field relations).

V. THE SHAPE OF THE MAIN GRANITE MASS

There is abundant evidence from the metamorphism of the sediments, the distribution of mineral veins and gravity anomalies that the major granite outcrops are connected at depth, and a number of authors have written of a " granite ridge " or " ridges " (e.g., Davison 1930; Hosking 1951, 1962). The space-form of the main mass of sub-surface granite has given rise to some speculation, however, and must obviously be related to the tectonic pattern as a whole.

Reference (see above, page 149) has been made to the fact that the granite outcrops tend to have steeply-dipping contacts along their southern margins and gently-dipping contacts to the North (Ussher *et al.* 1909; Reid *et al.* 1910) and these, together with the orientation of the feldspar megacrysts led Brammall (1926A) to conclude that the Dartmoor granite had been emplaced by a magma rising steeply in the south and then flowing nearly horizontally northwards; the sill-like form of some of the Dartmoor varieties reinforces this view. Ghosh (1934, p. 270) described a similar asymmetric flow pattern in the Type 1 granite of Carnmenellis.

The distribution of gravity anomalies over most of the south-western peninsula and of magnetic anomalies over Devon not only support the suggestion that the main granite " ridge " is asymmetrical but led Bott *et al.* (1958) to postulate a possible model for the Dartmoor granite. This model has the shape of an inverted "L" with its vertical limb to the south and its horizontal limb pointing north. The suggested thickness of the horizontal limb is 10 km. and the vertical limb is thought to extend to a depth of 15 km. to 20 km., both measurements being taken from sea level.

It is our view that such a model is not incompatible with much of the observed variation in the chemistry and mineralogy of the granites seen at the surface. Brammall and Harwood (1932), Ghosh (1927, 1934), and Bott *et al.* (1958) have all drawn attention to the importance of the contamination of the magma by assimilated country rock, and the word " stoping " has been used by some authors. One of us (Exley 1961A) has suggested that the stoping process would result in an outer envelope of contaminated, potash-rich magma within which a core of more sodic and volatile-rich magma could evolve by differentiation. At the weak region in the vicinity of the " hinge " of the " L ", the inner material might break out and would then give rise to the " later " rocks, some of which are particularly well seen in the western and central parts of the St. Austell granite.

Scott (1962) has described how the asymmetric distribution of gravity anomalies in the Land's End granite has been correlated with the fine-grained granite there; this may mean that Bott *et al.'s* "L"-shaped model is no longer acceptable, but further study is required before the general proposition of thick, steeply-inclined granite in the south and thinner, flat-lying granite in the north is discarded altogether.

VI. ALTERATION OF THE GRANITES

Almost by tradition, the main kinds of alteration in the granitic rocks of south-west England are grouped under the three heads of tourmalinization, greisening and kaolinization. It is proposed to follow this grouping in this account, although cases could be made out for considering the main processes in chronological or genetic terms.

1. Tourmalinization.

The presence of tourmaline is almost characteristic of the granitic rocks and mineral veins of south-west England. For many years, it has been recognized that there are at least two generations of this mineral in many rocks; in some mineral veins there may be many more than two generations.

In their comprehensive guide to the development of tourmaline in the Dartmoor granite, Brammall and Harwood (1925) distinguish between pre- and post-consolidation generations, and subdivide the first of these into primary and secondary groups. However, the term pre-consolidation carries with it the implication that magma was present, whereas (as we have already shown) the evidence for the replacement of an already reconstituted fabric indicates autometasomatism due to a *fluid* phase whose nature is uncertain. This may have been a tenuous magma or an aqueous fluid. As it is not possible to state exactly what is meant by pre-consolidation and post-consolidation, it is proposed to refer to early tourmaline (brown and blue in thin section) as *pre-joint* or *primary,* and the later tourmaline (blue-green in thin section) as *post-joint* or *secondary.*

(a) PRE-JOINT, PRIMARY TOURMALINE

This includes both the " primary " and " secondary " pre-consolidation tourmaline generations of Brammall and Harwood (1925). The former occurs as minute inclusions in biotite and associated with similarly-sized crystals of zircon, apatite and monazite. The latter forms the more common large, often irregular grains which may reach several millimetres in length. They are regarded as "secondary" by Brammall and Harwood on the grounds that they replace or envelop other minerals, in particular biotite and feldspar. These grains are usually black in hand specimen and range from blue to yellow or brown in thin section; not uncommonly they are zoned with blue cores and brown rims. Such crystals, if well-developed, are prismatic and may show triangular cross-sections, but more commonly they are

TABLE 10: *Tourmaline content of the granitic rocks of south west England*

Dartmoor
- (1) Stage I, scanty—nil; Stage II, abundant—very abundant; Stage III, abundant—very abundant. Stage IV, very abundant.
  (Brammall and Harwood 1925)
- (ii) Stage II, 0.9%*; Stage III, 2.7%.*
  (Brammall and Harwood 1932)

Bodmin Moor
- (i) Normal, " invariably present "; Godaver, " a larger development ". Fine, " much larger in amount ".
  (Ghosh 1927)
- (ii) Coarse, 0.3%—1.8%, mean 0.9%; Fine, 0.5%—2.7%, mean 1.3%.
  (Exley unpublished)

St. Austell
- (i) Biotite—muscovite, 1.2%; Lithionite, 2.4%; Gilbertite, 0.8%.
  (Richardson 1923)
- (ii) Biotite—muscovite, 1.3%; Early (porphyritic) lithionite, 3.8%; Late (non-porphyritic) lithionite, 0.1%; Fluorite, 0.1%.
  (Exley 1959)

Carnmenellis
- (i) Type 1, " seldom absent " but " scanty "; Type 2, no information; Type 3, " tourmaline is more abundant than in the earlier granites ".
  (Ghosh 1934)
- (ii) Type 1, 0.7%—1.0%, mean 0.8%; Type 2, 0.5%—1.8%, mean 1.0%; Type 3, 1.0%—1.8%, mean 1.4%.
  (Austin 1960)

Tregonning-Godolphin

Godolphin granite, tr.—1.3%, mean 0.8%; Tregonning granite, 1.0%—4.3%, mean 2.1%; Leucogranites, 0%—1.5%, mean 1.0%; Aplites, 0%—0.7%, mean 0.3%.
(Stone, unpublished)

Land's End

Coarse, 0%—4.6%, mean 1.5%; Medium, 0%—2.6%, mean 0.8%; Fine, 0.9%—3.3%, mean 1.8%.
(Booth, unpublished)

Scilly Isles
- (i) Stage 2A, 1.64%; Stage 2B, 1.58%; Stage 3, 0.92%. (Osman 1928).
- (ii) G1, 0.3%; G2, 0.7%. (Jones 1963).

*Weight per cent. All other values stated as volume per cent.

interstitial and anhedral. Tourmaline-rich nodules which are believed to fall into this category (see Brammall and Harwood 1925) occur in some of the granites; e.g., the Stage 3 ("Blue" granite of Dartmoor) and the fine-porphyritic biotite granite of Carnmenellis.

The amounts of *primary* tourmaline found in the granites are indicated in Table 10. From these data, which are arranged in what the various authors regard as the chronological order of granite types, it is apparent that there is a tendency

TABLE 11: *Chemical analyses of some tourmalines*

Weight per cent	1	2	3	ppm	4	5	6	7
SiO_2	35.20	36.36	36.10	B	5.53%			
TiO_2	0.51	tr	0.44	Ga	250	150	800	600
Al_2O_3	28.49	40.48	34.52	Cr	15	2	*	8
Fe_2O_3	0.79	—	n.d.	V	10	30	*	25
FeO	11.55	3.64	13.00	Sn	20	*	*	*
MnO	0.07	1.05	n.d.	Li	80	230	380	350
MgO	5.63	0.09	1.62	Ni	8	10	*	10
CaO	2.75	0.67	0.58	Co	20	*	*	25
Na_2O	2.12	2.20	1.73	Zr	55	*	*	*
K_2O	0.13	0.44	0.34	Mn	100	630	> 1000	600
Li_2O	0.08	1.27	—	Y	600	*	*	*
B_2O_3	8.82	10.30	9.45	Pb	*	60	70	65
H_2O+	3.52	3.64	1.67	Ba	*	10	*	60
H_2O-	0.07	0.08						
F	0.08	0.10	—					
	99.81	100.32						
Less O – =F	0.03	0.04						
	99.78	100.28	99.45					

1. Tourmaline from altered dolerite, St. Ives (Analysis 7, Table 51, Vol. 1. Deer, Howie and Zussman 1962).
2. Tourmaline from aplite, Meldon, Dartmoor (Analysis 6, Table 52, Vol. 1. Deer, Howie and Zussman 1962).
3. Tourmaline from fine granite, Bolitho, Carnmenellis (Analysis 26, Ghosh 1934).
4. Tourmaline from adamellite, Bosahan, Carnmenellis (Analysis 1 (T), Table 2, Butler 1953).
5. Tourmaline from pegmatite, Meldon, Dartmoor (Analysis 7 (T), Table 2, Butler 1953).
6. Tourmaline from pegmatite, Tresayes, St. Austell (Analysis 8 (T), Table 2, Butler 1953).
7. Tourmaline from topazfels, St. Mewan, St. Austell (Analysis 9 (T), Table 2, Butler 1953).

*Below limit of sensitivity.

for the amount of tourmaline to increase with time. This increase tends to be accompanied by increases in topaz and/or fluorite, and points to an increase in volatile content in the later stages of emplacement. At the same time, some granites—notably the younger St. Austell and Tregonning-Godolphin varieties—show a decrease in tourmaline content. These are rocks in which the femic constituents have a low concentration and in which the Na_2O/K_2O ratio is > 1; i.e., rocks which lie closer to the ternary minimum than those which contain more tourmaline. This suggests that the tourmaline-poor Na-rich terms may represent material which has escaped appreciable contamination from pelitic material, or has undergone a minimum amount of reconstitution under the influence of metasomatizing solutions.

Tourmaline in Cornwall is commonly referred to as " schorl " in the literature. From analyses 1, 3 and 4 of Table 11, it seems proper to use this term for *primary* tourmaline at least.

(b) POST-JOINT, SECONDARY TOURMALINE is the blue-green or green (in thin section) acicular variety spatially related to the joint system in the granite. As a rule, acicular tourmaline is not found in granite more than a few inches from a vein but there are exceptional occurrances, one of the best known of which is the rock type known as " luxullianite ", described by Wells (1946). In this rock, the only remaining constituents are quartz, microperthite and tourmaline, with accessory apatite, zircon and perhaps topaz. There is some question as to whether biotite was ever present (this point will be referred to below), but any original plagioclase has been replaced and the microperthite is much clouded and corroded. Most of the quartz has been recrystallized, whilst the *primary* tourmaline has been corroded and has acted as nuclei for the *secondary* tourmaline needles which now radiate throughout the rock.

A similar rock, but one in which no original minerals except a few relics of brown tourmaline remain, is the quartz-tourmaline rock of Carngrey near St. Austell (Flett 1909). This rock differs from another, perhaps more famous, example at Roche on the north side of the St. Austell granite in containing much blue-green secondary tourmaline, whilst the Roche rock contains only brown and blue tourmaline. Possibly the latter is primary.

Analyses 3, 5, 6 and 7 of Table 11 suggest that there is probably a case for regarding the blue-green secondary tourmaline as elbaite; certainly, it appears to lie towards the elbaite end of the schorl-elbaite series, and shows chemical features characteristic of a late-stage generation.

(c) THE TOURMALINIZATION PROCESS. The replacement of other minerals by tourmaline, whether before or after consolidation of the granites, involves considerable chemical changes. Several writers (Scrivenor 1903; Flett and Dewey 1912; Brammall and Harwood 1925) have noted a reciprocal relation between biotite and tourmaline, although Richardson (1923) is doubtful about this relation in the St. Austell granite. Brammall and Harwood suggest that tourmaline has replaced biotite, particularly in basic segregations, at a fairly early stage in crystallization, to form tourmaline bearing nodules, which later became nuclei for more extensive tourmalinization. Supporting evidence is provided by the distribution of titanium from the biotite; at high (magmatic) temperatures this is regarded as contributing to the high sphene and rutile content of the nodules, whereas at low temperatures it gave rise to anatase and brookite (Brammall and Harwood 1923, 1925).

Of the elements displaced by the tourmalinization process, perhaps the most important is potassium, especially where feldspar is involved. Brammall and

Harwood suggest that this element might have provided the excess needed by the magma to form mica from assimilated xenoliths. The instability of the tourmaline-biotite association in the Tregonning granite has been indicated by Stone (1963). Pelitic xenoliths in this granite show a transformation from biotite in the centre to lithionite associated with dark tourmaline at the edges. It is suggested that, in the presence of lithium and boron, the biotite of the xenoliths has undergone an ion exchange process whereby iron has been replaced by lithium and aluminium, and the excess iron released has been fixed in tourmaline. In this way, biotite (all of which may have been derived from xenoliths and walls; see pp. 137, 161 and 164 of this paper) is represented by the lithionite-tourmaline association in the later St. Austell and Tregonning-Godolphin granite terms.

2. **Greisening.**

(a) PRIMARY

Like tourmalinization, greisening may be separated into pre- and post-joint, or primary and secondary phases. Examples of the former are rare and are concentrated in the later varieties of granite. Exley (1959) has described the changes involved, which are restricted to the alteration of perthitic feldspar to pseudomorphous aggregates of white mica and quartz. Changes in both mineral and chemical composition in fluorite granites from St. Austell are quoted in Table 12. A late-stage form of greisening in which alteration affected minerals in zones of weakness has been described by Exley (1961B) from the Bodmin Moor granite.

(b) SECONDARY greisening is very common in south-west England and is closely related to the joint and mineral lode systems. The rocks of this generation are often true greisens, consisting only of quartz and white mica with perhaps a little accessory tourmaline and fluorite. Topaz is usually present and may be a major constituent (Flett, 1909).

Greisen veins tend to be concentrated near to the margins of the granites and are more common in the heavily mineralized area of Cornwall west of the St. Austell granite. In most cases, greisening is clearly the result of the alteration of the wall rocks of joints by late-stage solutions, so that a series of gradual changes from fresh granite through altered granite to greisen can frequently be traced. Detailed descriptions are given by Reid and Flett (1907) and Flett (1909). It is often the case that the central part of the vein contains quartz and some such mineral as wolframite or cassiterite, as in the well-known examples at Cligga Head.

(c) THE GREISENING PROCESS

There are few mineral or chemical analyses of greisened granites from south-west England. Experimental work by Noll (1932, 1936), Norton (1939), and Gruner (1929, 1944) shows that the breakdown of feldspar, especially alkali feldspar, and the subsequent synthesis of mica depend upon temperature, pressure, pH and the relative concentrations of the participating components. More recent chemical equilibrium studies by Hemley (1959) define more exactly the broader conclusions

TABLE 12: *Analyses of some greisened granites*

	1	2	3	4	5	6
Quartz	33.8	32.6	37.0	42.6		
Potash feldspar	7.6	5.0	6.3	1.9		
Albite	40.2	41.5	31.4	30.2		
Primary mica	7.7	7.0	6.3	6.5		
Secondary mica	8.7	12.7	16.4	17.5		
Fluorite	0.8	0.1	2.0	0.8		
Topaz	0.5	0.3	0.5	0.5		
Apatite	0.1	0.2	tr	nil		
Tourmaline	0.6	0.5	nil	nil		
% by volume	100.0	99.9	99.9	100.0		
Weight per cent						
SiO_2	72.1	73.8	72.2	74.4	70.17	69.42
TiO_2	0.09	0.09	0.06	0.05	0.41	tr
Al_2O_3	14.8	15.5	15.1	14.7	15.07	15.65
Fe_2O_3†	0.28	0.38	0.20	0.19	2.87	4.91
MgO	0.15	0.19	0.08	0.08	1.11	1.02
CaO	2.5	1.0	3.0	0.78	1.13	0.63
Na_2O	4.79	4.96	3.45	3.05	2.69	0.27
K_2O	2.54	2.68	3.01	3.02	5.73	4.06
P_2O_5	n.d.	n.d.	n.d.	n.d.	0.34	0.40
B_2O_3	n.d.	n.d.	n.d.	n.d.	strong tr	0.59
H_2O+	n.d.	n.d.	n.d.	n.d.	0.70	0.54
H_2O-	—	—	—	—	0.18	0.06
Cl	n.d.	n.d.	n.d.	n.d.	0.06	tr
F	2.0	0.13	0.84	0.12	0.15	3.36
S	n.d.	n.d.	n.d.	n.d.	0.04	—
Parts per million						
Li	29	31	27	31	510‡	3760‡
Rb**	255	270	430	385	—	—
Sr	32	41	44	65	—	—
Ba	35	40	125	100	—	—
V	9	8	14	10	—	—
Zr	*	*	42	42	—	—
Mn	30	45	30	30	93‡	3030‡

1. "Hard purple" fluorite granite, St. Austell (Column 1, Table V, Exley 1959).
2. "Mild purple" fluorite granite, St. Austell (Column 2, Table V, Exley 1959).
3. "Mild purple" fluorite granite, St. Austell (Column 3, Table V, Exley 1959).
4. "Hard white" fluorite granite, St. Austell (Column 4, Table V, Exley 1959).
5. Granite, Lamorna, Land's End (Analysis 1, p. 59, Reid and Flett 1907).
6. Greisen with tourmaline and topaz, St. Michael's Mount (Analysis V, p. 59, Reid and Flett 1907).

*Below sensitivity of method.
†All Fe as Fe_2O_3.
‡Recalculated from percentage.
**Rb values revised to conform with later values for G1 and W1 (Fleischer and Stevens 1962).

of the earlier workers. Greisening may be said, in general terms, to take place approximately between 300° C and 500° C at pressures of the order of 150 Kg. per cm.[2], provided that there is a sufficient supply of "hydrogen" ions to aid the hydrolysis of the feldspars. Evidence that the solutions responsible for post-joint greisening contained fluorine is provided by increases in the amount of topaz in the greisened rocks with the frequent addition of fluorite, and by a comparison of analytical data (Table 12, analyses 5 and 6).

The importance of fluorine in the earlier pre-joint greisening phase is questionable, however. Analyses 2 and 4 of Table 12 show marked decreases in the amounts of the important fluorine-bearing minerals, topaz and fluorite, as compared with analyses 1 and 3. The argument that these minerals became unstable in a fluorine-rich environment and contributed their own fluorine to new secondary mica is effectively countered by the chemical analyses, which show large decreases in the amounts of total fluorine present in the more altered rocks. It must be supposed, therefore, that the acidity of the late-stage inter-granular fluid was not due in any significant measure to the presence of fluorine.

In view of the fact that perthite is the mineral mainly attacked during the earlier greisening phase, the small changes in the potash content of the rocks (analyses 1 to 4 of Table 12) are remarkable. In the first pair of analyses (Table 12), the calculated loss of potash from the perthite (*ca.* 0.5 cent) is almost exactly balanced by the potash incorporated into the extra secondary mica, and the increase of 0.14 per cent indicated by the chemical analyses can be accounted for by the greater amount of albite in the second rock. In the second pair, however, even when all the mineral variations have been considered, there ought to be a loss of potash amounting to about 0.2 per cent. That there is no such loss probably indicates that some secondary mica has not been accounted for in the mode. In both cases, it is evident that more secondary mica has been formed than could be synthesised from the potash feldspar alone: the differences in the ratios K_2O : Al_2O_3 : SiO_2 in feldspar and mica ensure an excess of K_2O when feldspar is altered. Much of the additional secondary mica has replaced topaz.

3. **Kaolinization.**

Largely because of its commercial implications, kaolinization in the granites has been studied in considerable detail, although much still remains to be explained. All the granite outcrops and associated elvans have been kaolinized to some extent and all the major intrusions except those of the Scilly Isles have been or are being worked for china clay. The most important areas of production at present are the south-western parts of Dartmoor and the central and western parts of the St. Austell granite.

It has long been recognized that kaolinization is a post-joint process, although it is possible that it occurred in more than one stage. The hypothesis that kaolinization is the result of weathering (e.g., Hickling 1908) has not had many supporters in recent years. Good evidence for a hydrothermal origin (Collins 1878, 1887, 1909; Geological Survey Officers 1907, 1909, 1910; Exley 1959, 1964) is provided

TABLE 13: *Analyses of some kaolinized granites*

	1	2	3	4	5	6
Quartz	33.7	37.9	27.1	33.8		
Potash feldspar	15.3	12.4	18.2	nil		
Albite	30.1	nil	4.6	nil		
Primary mica	8.3	4.0	10.9	9.6		
Secondary mica	10.3	15.1	20.7	22.7		
Clay-mica aggregates	nil	30.5	18.4	32.0		
Fluorite	1.0	nil	nil	nil		
Topaz	1.0	0.1	0.1	1.9		
Apatite	0.2	nil	nil	nil		
Tourmaline	0.1	0.1	tr	tr		
	100.0	100.1	100.0	100.0		
Weight per cent						
SiO_2	72.5	70.1	n.d.	68.9	70.17	71.15
TiO_2	0.09	0.10	0.05	0.09	0.41	0.16
Al_2O_3	15.2	18.6	n.d.	21.35	15.07	19.41
Fe_2O_3†	0.65	0.52	0.23	0.07	2.87	1.42
MgO	0.30	0.35	0.08	0.10	1.11	0.45
CaO	1.3	0.30	0.06	0.20	1.13	0.21
Na_2O	3.38	0.10	0.19	0.12	2.69	0.05
K_2O	4.16	4.69	6.95	2.63	5.73	1.44
P_2O_5	n.d.	n.d.	n.d.	n.d.	0.34	0.07
B_2O_3	n.d.	n.d.	n.d.	n.d.	strong tr	0.33
H_2O+	n.d.	n.d.	n.d.	n.d.	0.70	5.09
H_2O-	n.d.	n.d.	n.d.	n.d.	0.18	0.16
Cl	n.d.	n.d.	n.d.	n.d.	0.06	tr
F	0.45	0.17	0.3	1.0	0.15	0.11
S	n.d.	n.d.	n.d.	n.d.	0.04	—
Parts per million						
Li	24	38	24	62	510	100
Rb‡	490	390	690	40	—	—
Sr	66	111	34	95	—	—
Ba	99	82	100	52	—	—
V	9	9	8	9	—	—
Mn	55	45	*	42	930	700

1. Late lithionite granite, St. Austell (Analysis 1, Table VI, Exley 1959).
2. Kaolinized late lithionite granite, St. Austell (Analysis 4, Table VI, Exley 1959).
3. Kaolinized fluorite granite, St. Austell (Analysis 7, Table VII, Exley 1959).
4. Kaolinized fluorite granite, St. Austell (Analysis 9, Table VII, Exley 1959).
5. Granite, Lamorna, Land's End (Analysis 1, p. 59, Reid and Flett 1907).
6. Kaolinized granite, Georgia Works, Land's End (Analysis IV, p. 59, Reid and Flett 1907).

*Below sensitivity of method.
†All Fe as Fe_2O_3.
‡Rb values revised to conform with later values for G1 and W1 (Fleischer and Stevens 1962).

by the depth of alteration, the occurrence of kaolinized rocks beneath an impermeable cover (Collins, 1909), and the way in which the present surface has developed as a consequence of the distribution of fresh and altered rock (Reid *et al.* 1910).

The clay is derived from the decomposition of feldspar, plagioclase in particular. Potash feldspar is evidently stable in kaolinizing conditions until an advanced stage in the process: there are many examples of rocks worked for china clay in which the perthite is still quite fresh. Field evidence suggests that the manner of alteration, in which pseudomorphous aggregates of clay and hydrous secondary mica or illite are left after feldspar, is similar in all the granites.

Detailed examinations have been made on fresh and altered rocks from the St. Austell district by Exley (1959) and some analyses are summarized in Table 13. In the first case (analyses 1 and 2) the specimens were collected from rocks respectively close to and some five feet away from the veins through which the solutions responsible for alteration had moved. The antipathetic relation between albite and clay is quite clear from the analyses. Among the chemical changes, increases appear to be related to elements that are involved in the formation of secondary mica, and losses are related to ionic potential. In the second case, the specimens were collected from a greater distance apart (analyses 3 and 4, Table 13) and kaolinization has gone to a more extreme stage: potash feldspar as well as plagioclase has been eliminated. Here, gains and losses appear to be closely related to ionic potential, the critical value of which is 1.5 (Exley 1959). Chemical analyses of granites from Land's End show similar trends.

Further study of one of these sets of rocks from St. Austell and of others from Bodmin Moor and Dartmoor has shown that the degree of order in the new kaolinite crystals is greater near the channel from which the kaolinizing fluid entered the rock, and that there is some evidence that montmorillonite may form an intermediate mineral between the breakdown of feldspar and the formation of kaolinite close to the " front " of alteration (Exley 1964).

All the earlier writers postulated an acid solution as the kaolinizing agent and this has been substantiated by the work of Noll (1936), Gruner (1944) and Hemley (1959). Both boron and fluorine have been cited as important constituents of these acid solutions and there has been much discussion about the relation between tourmalinization and kaolinization (Reid and Flett 1907). However, there is evidence that fluorine diminished during alteration and that increases in boron are probably due to pre-existing late-stage tourmaline associated with the veins. There is also the important point that tourmaline veins are virtually absent from the Stannon Marsh clay district of Bodmin Moor (e.g., Reid *et al.* 1910). As an alternative, it is suggested that acid conditions were provided by dissolved silica, which on the evidence of quartz veins and silicified rocks must have been present in abundance.

4. **Chronology of the main phases of alteration.**

Overlap between the various kinds of alteration makes the construction of a time scale difficult. The effects of one process are often difficult to distinguish from the effects of another; e.g., both pre-joint tourmalinization and pre-joint greisening have affected the St. Austell granite. Both processes resulted in the destruction of feldspar and may have been either contemporaneous or alternative, the synthesis of tourmaline depending upon the concentration of boron in the inter-granular fluid at a given locality.

There is also uncertainty as to the age relations of the post-joint phases of tourmalinization and greisening. Again, it is possible that this is dependent upon the distribution and concentration of boron. However, in spite of the conclusion of Reid and Flett (1907 p. 58) that ". . . . the formation of schorl rock is the earlier and the greisening the later . . . ." the weight of evidence suggests the reverse. In many cases, tourmaline veins have selvedges of greisen and greisen veins have a development of tourmaline in their central parts. Both Osman (1928) and Hosking (1951) have no hesitation in regarding greisening as the earlier.

There remains some doubt regarding the kaolinization stage. Whilst generally admitting its low temperature origin, those authors who regard it as being dependent on boron-bearing solutions tend to regard it as penecontemporaneous with the formation of the youngest tourmaline veins. Others regard it as clearly post-tourmalinization (e.g., Exley 1959, 1964).

VII. CONCLUDING REMARKS

In the foregoing account, we have attempted to reconcile phenomena observed in the field and thin section and the data from experimental petrology. We have attempted also to review most of the work done on the granitic rocks of south-west England since the turn of the century. We have omitted most of the earlier work including the "classics" by De la Beche (1839) and Henwood (1843), not because they provide no basis for a synthesis of the origin of these granites, but because they have provided much of the basis of later studies and as a result have already been reviewed.

It is now clear that numerical data are necessary in the study of granite complexes; such data are far from sufficient in the rocks considered here, although work now in progress will no doubt help to remedy this deficiency.

We have divided the granites of south-west England into broad groups based upon the presence or absence of potash feldspar megacrysts, the grain size of the groundmass and the nature and amount of the dark mica. This subdivision provides a convenient field classification, but still requires a more rigorous testing to establish whether or not the field criteria are significant. Attempts to erect subdivisions of coarse porphyritic biotite granites from the Bodmin Moor (Ghosh 1927) and Carnmenellis (Ghosh 1934) masses are open to doubt (Austin 1960; Exley, unpublished) as is the case also with Osman's (1928) subdivision of the coarse porphyritic biotite granite of Scilly (D. L. Jones, personal communication). Field criteria appear to be insufficient to subdivide the coarse porphyritic biotite granites; numerical data are required in order to establish the significance of differences between types and variants.

Statistical investigations are required on a variety of scales, and work on a broad scale currently in progress on Bodmin Moor and Land's End, which has as one of its aims the computation of trend surfaces by multivariate analysis of modal data, should provide broad trends which might suggest where further more detailed work is required. On the other hand, work on the Tregonning granite is concerned with the detailed analysis of a small region in order to test the scales of homogeneity of a single " rock type ".

We envisage a palingenetic origin of the granites which is consistent with their regional setting and with the " granite series " of Read (1957). Selective fusion would result in a liquid having, initially, a composition close to the " natural " ternary minimum, " contaminated " by solid material not taken into solution, as well as xenolithic fragments. The density difference between the magma and its mantle would aid the upward rise of the former, partly by plastic deformation of the country rocks, partly by assimilative granitization, and partly by mechanical stoping (ref. Lacy 1960). At higher levels, crystallization of the bulk of the magma would have occurred; magma would be subordinate and interstitial and would pass continuously into interstitial aqueo-silicate fluid containing alkalis. Differentiation could have occurred in two ways:

(a) by crystal fractionation together with the gravitational removal of " contaminants ", resulting in a liquid having a composition near the natural ternary minimum, and

(b) by differentiation of the interstitial aqueo-silicate fluid.

The latter could result in the marked lithium and fluoride enrichment found in some of the granites, together with the removal of potassium and enrichment in sodium.

Whilst megacrysts of potash feldspar were growing, largely as a result of internal metasomatism as the temperature was falling, it is considered that the granites were emplaced into their present positions as sensibly solid bodies containing interstitial lubricating fluids.

Thus, it is reasonable to suppose that the granite variants have arisen in part from the magmatic differentiation of a contaminated liquid-crystal mush, and in part from ion-exchange reactions between the rock and late-stage fluids derived from magma. The occurrence of some features suggesting replacement and others pointing to a magmatic origin are thus resolved as resulting from dependent processes: replacement follows magmatism in the " granitization " of granities. Granitized granites have also been described by Härme (1958) in southern Finland, but in these cases the material responsible for granitization has been introduced as veins. Postmagmatic potash metasomatism has also been described by Eskola (1956).

Finally, there is no reason to suppose that there is a break between late-magmatic solutions and the hydrothermal solutions responsible for late-stage alteration process (cf. Tuttle and Bowen 1958, pp. 84-89). Alkali ion-exchange reactions in which the " hydrogen " ion participates would result in appreciable alkalinity at elevated temperatures (see Fyfe, Turner and Verhoogen 1958, pp. 142-148), but with falling temperature and the accompanying dissociation of " acid gases " the pH would fall within the range of hydrolysis of the feldspars resulting in greisening. Kaolinization seems to be less dependent on the presence of dissociated " acid gases ", the concentration of which appears to have been reduced by the earlier reactions.

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REFERENCES

AUSTIN, W. G. C. 1960. Some aspects of the geology of the Carnmenellis area, Cornwall. *M.Sc. thesis of the University of Birmingham* (unpublished).

BARROW, G. 1906. The Geology of the Isles of Scilly. *Mem. geol. Surv. U.K.*

BATTEY, M. H. 1955. Alkali metasomatism and the petrology of some keratophyres. *Geol. Mag.* **92,** 104-126.

BOTT, M. H. P., DAY, A. A. and MASSON-SMITH, D. 1958. The geological interpretation of gravity and magnetic surveys in Devon and Cornwall. *Phil. Trans. roy. Soc. Lond., Ser. A,* **251,** 161-191.

BOWEN, N. L. 1828. *The evolution of the igneous rocks.* Princeton Univ. Press.

BOWLER, C. M. L. 1958. The distribution of alkalis and fluorine across some granite—killas and granite—greenstone contacts. *Abstr., Proc.* 1958 *Conf. Geol. Geomorph. S.W. England.* R. geol. Soc. Cornwall, 20-21.

BRAMMALL, A. 1926A. The Dartmoor granite. *Proc. Geol. Ass. Lond.,* **37,** 251-277.

—— 1926B. Excursion to Dartmoor (*Report by the Director*). *Proc. Geol. Ass. Lond.,* **37,** 278-282.

—— and HARWOOD, H. F. 1923. The Dartmoor granite: its mineralogy, structure and petrology. *Miner. Mag.,* **20,** 39-53.

—— —— 1925. Tourmalinization in the Dartmoor granite. *Miner. Mag.,* **20,** 319-330.

—— —— 1932. The Dartmoor granites: their genetic relationships. *Quart J. geol. Soc. Lond.,* **88,** 171-237.

BUTCHER, N. E. 1961. Age of the orogeny and granites in south-west England. *Nature,* **190,** 253.

BUTLER, J. R. 1953. The geochemistry and petrology of rock weathering. (1) The Lizard area, Cornwall. *Geochim. et Cosmochim. Acta,* **4,** 157-178.

CHAYES, F. 1955. Modal composition of two facies of the Carnmenellis granite. *Geol. Mag.,* **92,** 364-366.

—— 1956. *Petrographic modal analysis.* New York (Wiley).

—— 1962. Numerical correlation and petrographic variation. *J. Geol.,* **70,** 440-452.

—— and SUZUKI, Y. 1963. Geological contours and trend surfaces (A discussion). *J. Pet.,* **4,** 307-312.

COE, K. 1958. The plutonic geology of the Mount Leinster district. *Ph.D. thesis of the Trinity College, Dublin* (unpublished).

COLLINS, J. H. 1878. *The Hensbarrow granite district.* Truro (Lake & Lake).
—— 1887. On the nature and origin of clays: the composition of kaolinite. *Miner. Mag.*, **7**, 205-214.
—— 1909. Geological features visible at Carpalla china clay pit. *Quart. J. geol. Soc. Lond.*, **65**, 155-161.
—— 1912. Observations on the west of England mining region. *Trans. R. geol. Soc., Cornwall*, **14**.
CUNDY, E. K., WINDLE, W. and WARREN, I. H. 1960. The occurrence of zinnwaldite in Cornwall. *Clay Minerals Bull.*, **14**, 151-156.
DAVISON, E. H. 1930. *Handbook of Cornish geology. 2nd Edit.*, Truro (Oscar Blackford).
DEARMAN, W. R. and BUTCHER, N. E. 1959. The geology of the Devonian and Carboniferous rocks of the north-west border of the Dartmoor granite, Devonshire. *Proc. Geol. Ass. Lond.*, **70**, 5-92.
DEER, W. A., HOWIE, R. A. and ZUSSMAN, J. 1962. *Rock-forming minerals.* London (Longmans).
DE LA BECHE, H. T. 1839. *Report on the geology of Cornwall, Devon and west Somerset.* London.
DINES, H. G. 1956. The metalliferous mining region of south-west England. *Mem. geol. Surv. U.K.*
ESKOLA, P. 1956. Postmagmatic potash metasomatism of granite. *Bull. Comm. géol. Finlande*, **172**, 85.
EXLEY, C. S. 1956. The formation of china stone and china clay in the St. Austell granite. *Brit. Ceram. Research Assoc. Research Paper No. 331.*
—— 1959. Magmatic differentiation and alteration in the St. Austell granite. *Quart. J. geol. Soc. Lond.*, **114**, 197-230.
—— 1961A. Relationships and origins of the south-western granites. *Abstr. Proc.* 1961 *Conf. Geol. Geomorph. S.W. England.* R. geol. Soc. Cornwall, 4-5.
—— 1961B. A note on greisening in the Bodmin Moor granite. *Geol. Mag.*, **98**, 427-430.
—— 1963. Quantitative areal modal analysis of granitic complexes: a further contribution. *Bull. geol. Soc. Amer.*, **74**, 649-654.
—— 1964. Some factors bearing on the natural synthesis of clays in the granites of south west England. *Clay Minerals Bull.*
FLEISCHER, M. and STEVENS, R. E. 1962. Summary of new data on rock samples G-I and W-I *Geochim. et Cosmochim. Acta*, **26**, 525-543.
FLETT, J. S. 1909. In Ussher, Barrow and MacAlister, 1909.
—— SIR J. S. 1946. Geology of the Lizard and Meneage. 2nd Edit. *Mem. geol. Surv. U.K.*
—— and DEWEY, H. 1912. In Reid *et al.*, 1912.
FLOYD, P. A. 1962. Geology of the Land's End aureole from Tater-du to Newlyn, Cornwall. *Ph.D thesis of the University of Birmingham* (unpublished).
FYFE, W. S., TURNER, F. J. and VERHOOGEN, J. 1958. Metamorphic reactions and metamorphic facies. *Mem. geol. Soc. Amer. No. 73*, 259 pp.
GHOSH, P. K. 1927. Petrology of the Bodmin Moor granite (eastern part), Cornwall. *Miner. Mag.*, **21**, 285-309.
—— 1934. The Carnmenellis granite: its petrology, metamorphism and tectonics. *Quart. J. geol. Soc. Lond.*, **90**, 240-276.
GRUNER, J. W. 1939. Formation and stability of muscovite in acid solutions at elevated temperatures. *Amer. Min.*, **24**, 624-628.
—— 1944. Hydrothermal alteration of feldspars in acid solutions between 300° and 400°C. *Econ. Geol.*, **39**, 578-589.

HALL, S. 1930. The geology of the Godolphin granite. A study of the coastal geology between Perranuthnoe and Loe Pool. *Proc. Geol. Ass. Lond.*, **41**, 117-147.

HÄRME, M. 1958. Examples of the granitization of plutonic rocks. *Compt. Rend. Soc. géol. Finlande* **30**, 45-64.

HARRY, W. T., and EMELEUS, C. H. 1960. Mineral layering in some granite intrusions of S.W. Greenland. *Rept. Internat. Geol. Cong., Norden*, Part 14, 172-181.

HEMLEY, J. J. 1959. Some mineralogical equilibria in the system $K_2O - Al_2O_3 - SiO_2 - H_2O$. *Amer. J. Sci.*, **259**, 241-270.

HENDRIKS, E. M. L. 1937. Rock succession and structure in south Cornwall: a revision, with notes on the central European facies and Variscan folding there present. *Quart. J. geol. Soc. Lond.*, **93**, 322-360.

HENWOOD, W. J. 1843. On the metalliferous deposits of Cornwall and Devon. *Trans. R. geol. Soc. Cornwall*, **5**.

HICKLING, G. H. 1908. China clay: its nature and origin. *Trans. Inst. Min. Eng.*, **36**, 10-33.

HILL, J. B. 1901. The plutonic and other intrusive rocks of west Cornwall in their relation to the mineral ores. *Trans. R. geol. Soc. Cornwall*, **12**, 1-71.

—— 1913. The geology of northern Meneage. *Proc. Geol. Ass. Lond.*, **24**, 134-158.

—— AND MACALISTER, D. A. 1906. The geology of Falmouth and Truro and of the mining district of Camborne and Redruth, *Mem. geol. Surv. U.K.*

HOSKING, K. F. G. 1951. Primary ore deposition in Cornwall. *Trans. R. geol. Soc. Cornwall*, **18**, 309-356.

—— 1952. Cornish pegmatites and bodies with pegmatite affinities. *Trans. R. geol. Soc. Cornwall*, **18**, 411-455.

—— 1954. The pegmatites of Trolvis quarry, Carnmenellis, Cornwall. *Geol. Mag.*, **91**, 273-285.

—— 1962. The relationship between the primary mineralization and the structure of south-west England. *Some aspects of the Variscan fold belt*, Manchester.

JAHNS, R. H. 1955. The study of pegmatite deposits. *Econ. Geol.*, 50th Anniversary Vol., 1025-1130.

JONES, D. L. 1963. The accessory minerals of the Scilly Isles granites. *Proc. Ussher Soc.*, **1**, Part 2, 46-50.

LACY, E. D. 1960. Melts of granitic composition, their structure, properties and behaviour. *Rept. Internat. Geol. Cong., Norden*, Part 14, 7-15.

LAMBERT, J. L. M. 1959. Cross-folding in the Gramscatho Beds at Helford River, Cornwall. *Geol. Mag.*, **96**, 489-496.

LEVINSON, A. A. 1953. Studies in the mica group: relationships between polymorphism and composition in the muscovite-lepidolite series. *Amer. Min.*. **38**, 88-107.

LINK, R. F. and KOCH, G.S. 1962. Quantitative areal modal analysis of granitic complexes: a discussion. *Bull. geol. Amer.*, **73**, 411-414.

LONG, L. E. 1962. Some isotopic ages from south west England. *Some aspects of the Variscan fold belt*. Manchester.

MACKENZIE, W. S. 1960. Review of some contributions of experimental studies to petrology. *Lpool. and Manchr. geol. J.*, **2**, 369-388.

—— and SMITH, J. V. 1962. Single crystal X-ray studies of crypto- and microphertites. *Norsk Geol. Tidsskr.*, **42** (Feldspar Volume), 72-103.

MACKINTOSH, D. M. 1963. Superimposed folding in Namurian turbidite sandstones near St. Gennys, north Cornwall. *Proc. Ussher Soc.*, **1**, Part 2, 74-76.

MILLER, J. A. and MOHR, P. A. 1964. Potassium-Argon measurements on the granites and some associated rocks from south-west England. *Geol. J.*, **4**, 105-126.

NOLL, W. 1932. Hydrothermal synthese des Muscovits. *Nachtr. Geo. Wiss. Gottingen*, **20**, 122-134.

—— 1936. Ueber die Bildungsbedingungen von Kaolin, Montmorillonit, Sericit, Pyrophyllit, and Analcim. *Mineraolg. petrog. u. mitt.*, **48**, 210-246.

NORTON, F. H. 1939. Hydrothermal formation of clay minerals in the laboratory. *Amer. Min.*, **24**, 1-17.

OEN, Soen, Ing. 1960. The intrusion mechanism of the late- Hercynian post-tectonic granite plutons of northern Portugal. *Geol. en Mijnb.*, **22**, 257-296.

ORVILLE, P. M. 1959. Feldspars. In *Ann. Rept. Dir. Geophys. Lab., Carnegie Inst. Washington Year Book*, **58**.

—— 1960. Petrology of several pegmatites in the Keystone District, Black Hills, South Dakota. *Bull. geol. Soc. Amer.*, **71**, 1467-1489.

—— 1963. Alkali ion exchange between vapour and feldspar phases. *Amer. J. Sci.*, **261**, 201-237.

OSMAN, C. W. 1928. The granites of the Scilly Isles and their relation to the Dartmoor granites. *Quart. J. geol. Soc. Lond.*, **84**, 258-292.

PHILLIPS, J. A. 1875. The rocks of the mining districts of Cornwall and their relation to metalliferous deposits. *Quart. J. geol. Soc. Lond.*, **31**, 319-345.

PITCHER, W. S. and READ, H. H. 1959. The main Donegal granite. *Quart. J. geol. Soc. Lond.*, **114**, 259-305.

READ, H. H. 1955. Granite series in mobile belts. In Poldervaart, A. (Edit.). Crust of the earth. *Spec. Pap. geol. Soc. Amer.*, **62**, 409-430.

—— 1957. *The granite controversy.* London (Murby).

—— 1958. Donegal granite. *Sci. Prog.*, **46**, 225-240.

REID, C. and FLETT, J. S. 1907. The geology of the Land's End district. *Mem. geol. Surv. U.K.*

REID, C., BARROW, G., and DEWEY, H. 1910. The geology of the country around Padstow and Camelford. *Mem. geol. Surv. U.K.*

—— —— and OTHERS. 1911. The geology of the country around Tavistock and Launceston. *Mem. geol. Surv. U.K.*

—— and OTHERS. 1912. The geology of Dartmoor. *Mem. geol. Surv. U.K.*

RICHARDSON, W. A. 1923. A micrometric study of the St. Austell granite. *Quart. J. geol. Soc., Lond.*, **79**, 546-576.

ROBSON, J. 1945. The structure of Cornwall. *Trans. R. geol. Soc. Cornwall*, **17**, 227-246.

SCHALLER, W. T. 1925. The genesis of lithium pegmatites. *Amer. J. Sci.*, 5th Ser., **10**, 269-279.

SCOTT, P. 1962. A gravity survey in South West Cornwall. *Proc. Ussher. Soc,.* **1**, Part 1, 18-19.

SCRIVENOR, J. B. 1903. The granite and greisen of Cligga Head (Western Cornwall.) *Quart. J. geol Soc. Lond.*, **59**, 142-159.

SIMPSON, S. 1960 Structures of Devon and Cornwall. *Geol. Mag.*, **99**, 284-285.

STAATZ, M. H. and TRITES, A. F. 1955. Geology of the Quartz Creek pegmatite district, Gunnison County, Colorado, *U.S. geol. Surv. Prof. Paper 265*, 111 pp.

STONE, M. 1960. The Tregonning-Godolphin granite. *Abstr. Proc.* 1960, *Conf. Geol. Geomorph. S.W. England.* R. geol. Soc. Cornwall, 13.

—— 1961. Genesis of the granites of south-west England. *Abstr. Proc.* 1961, *Conf. Geol. Geomorph. S.W. England.* R. geol. Soc. Cornwall, 5-6.

—— 1962. Vertical flattening in the Mylor Beds, near Porthleven, Cornwall. *Proc. Ussher Soc.*, **1**, Part 1, 25-27.

—— 1963. Lithium in the Tregonning-Godolphin granite. *Proc. Ussher Soc.*, **1**, Part 2, 50-53.

—— and Austin, W. G. C. 1961. The metasomatic origin of the potash feldspar megacrysts in the granites of south-west England. *J. Geol.*, **69**, 464-472.

Subbarao, G. 1960. A study of the Godolphin granite, with special reference to its structure. *Abstr. Proc.* 1960, *Conf. Geol. Geomorph. S.W. England.* R. geol. Soc. Cornwall, 15-17.

Tuttle, O. F. 1952. Origin of the contrasting mineralogy of extrusive and plutonic salic rocks. *J. Geol.*, **60**, 107-124.

—— and Bowen, N. E. 1958. Origin of granite in the light of experimental studies in the system $NaAlSi_3O_8$—$KAlSi_3O_8$—SiO_2—H_2O. *Geol. Soc. Amer. Mem.*, **74**, 153 pp.

Uspensky, N. M. 1943. On the genesis of granitic pegmatites. *Amer. Min.*, **28**, 437-447.

Ussher, W. A. E. 1912. The geology of the country around Ivybridge and Modbury. *Mem. geol. Surv. U.K.*

—— Barrow, G. and MacAlister, D. A. 1909. The geology of the country around Bodmin and St. Austell. *Mem. geol. Surv. U.K.*

Wells, M. K. 1946. A contribution to the study of luxullianite. *Miner. Mag.*, **27**, 186-194.

Whitten, E. H. T. 1959. Composition trends in a granite: modal variation and ghost stratigraphy in part of the Donegal granite, Eire. *Journ. Geophys. Research*, **64**, 835-848.

—— 1961. Systematic quantitative areal variation in five granitic massifs from India, Canada and Great Britain. *J. Geol.*, **69**, 619-646.

—— 1962. Sampling and trend surface analysis of granites: a reply. *Bull. geol. Soc. Amer.*, **73**, 415-418.

—— 1963. A reply to Chayes and Suzuki. *J. Pet.*, **4**, 313-316.

Winchell, A. N. 1951. *Elements of optical mineralogy.* Part II. New York (Wiley).

Windley, B. 1963. The plutonic development of the Sardloq area, S.W. Greenland. *Ph.D. thesis of the University of Exeter* (unpublished).

Worth, R. H. 1902. The petrography of Dartmoor and its borders, Part 1. *Trans. Devon Ass.*, **34**, 496-527.

—— 1903. The petrography of Dartmoor and its borders, Part 2. *Trans. Devon. Ass.*, **35**, 759-767.

Wyllie, P. J. and Tuttle, O. F. 1961. Experimental investigation of silicate systems containing two volatile components. Part II. The effects of NH_3 and HF, in addition to H_2O on the melting temperatures of albite and granite. *Amer. J. Sci.*, **259**, 128-143.

Yoder, H. S., Stewart, D. B. and Smith, J. R. 1957. Ternary feldspars. *Ann. Rept. Dir. Geophys. Lab., Carnegie Inst. Washington Year Book*, **56**, 206-214.